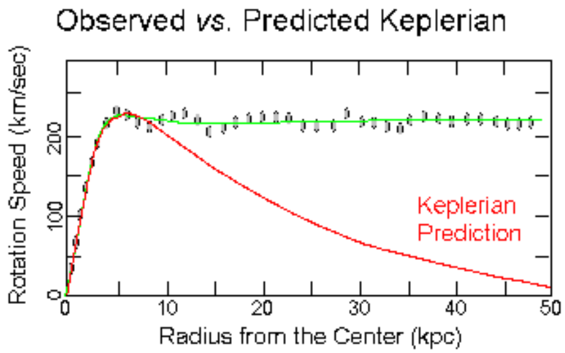
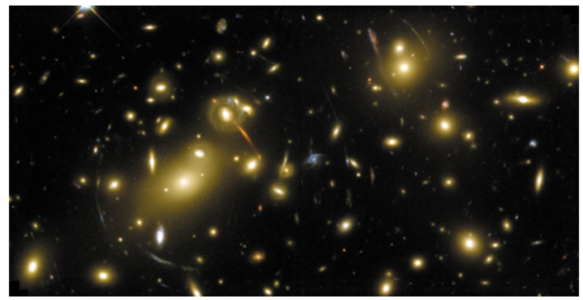
S. Stone
Sept. 2012

New Physics from Flavour

Reasons for Physics Beyond the Standard Model

- Dark Matter





Gravitational lensing

- Dark Energy: Cosmological constant
- Hierarchy Problem: Divergent quantum corrections to go from Electroweak scale ~100 GeV to Planck scale of Energy ~10^{19} GeV without "fine tuning" quantum corrections
- *All of the above may only be related to Gravity*

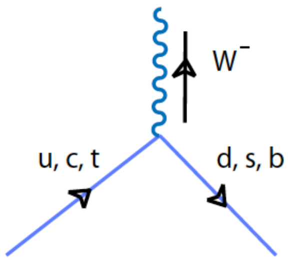
Reasons for NP

- Flavor problem: Why 3 replications of quarks & leptons?
- Baryogenesis: The amount of CP Violation observed thus far in the quark sector is too small: $(n_B - n_{\bar{B}})/n_\gamma = \sim 10^{-20}$ but $\sim 6 \times 10^{-10}$ is needed. Thus New Physics must exist to generate needed CP Violation
- To explain the values of CKM couplings, V_{ij}, (both neutrino & quark)
- To explain the masses of fundamental objects. Are they related to the V_{ij}'s?

Quark Mixing & CKM Matrix

- In SM charge -1/3 quarks (d, s, b) are mixed
- Described by CKM matrix (also ν are mixed)

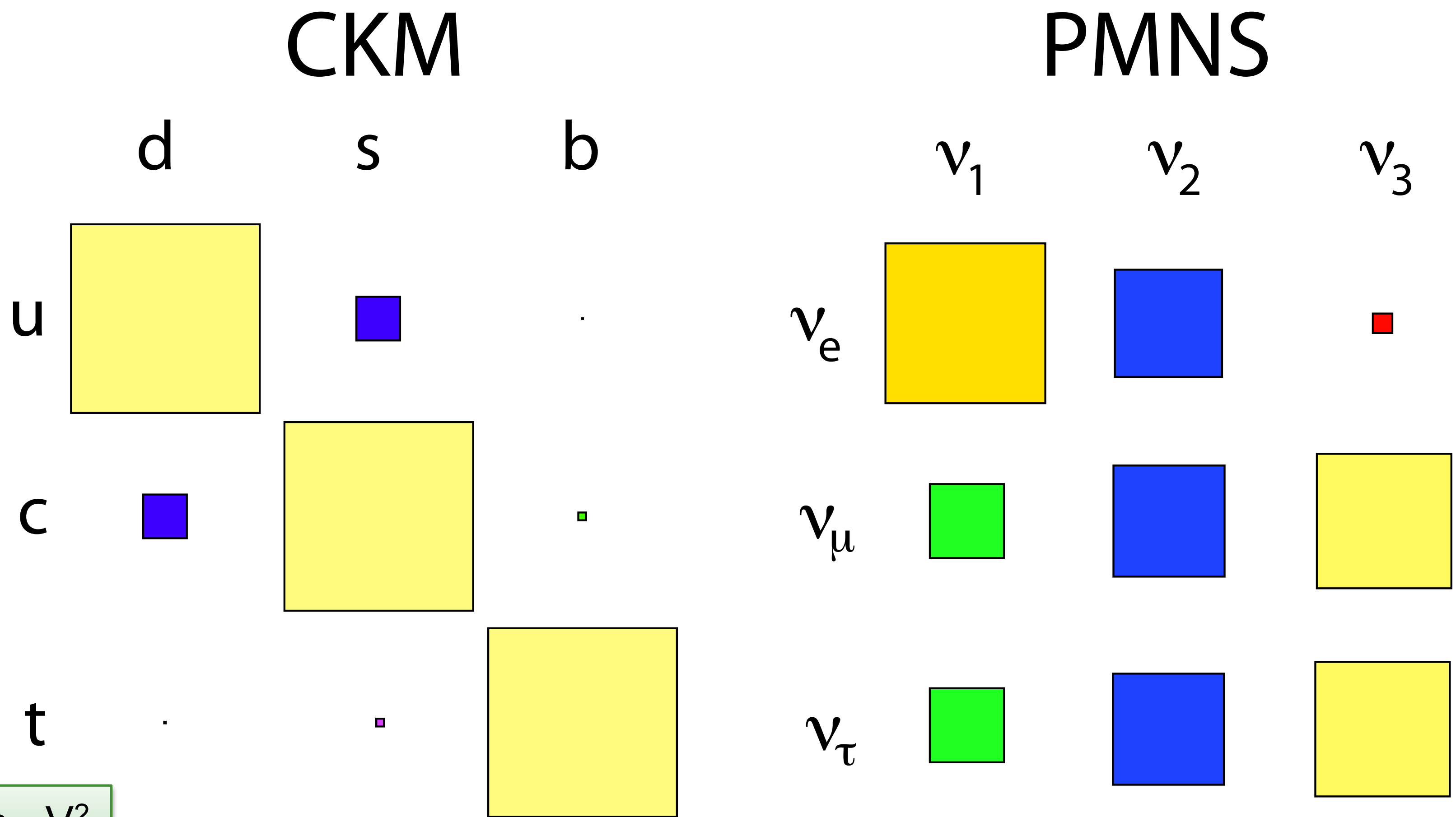
$$V_{\left(\frac{2}{3},-\frac{1}{3}\right)} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



$$= \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

- λ=0.225, A=0.8, constraints on ρ & η
- These are fundamental constants in SM

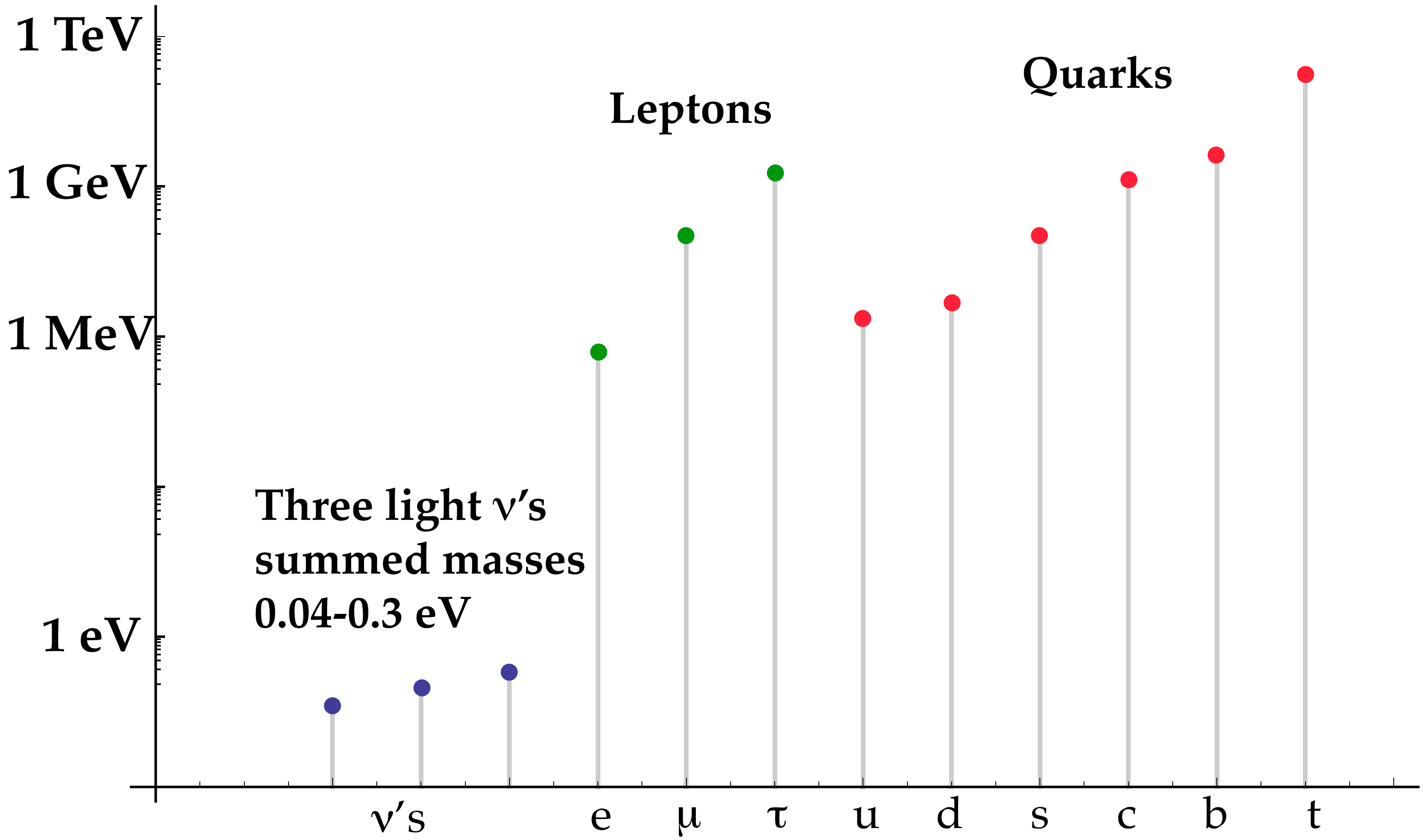
CKM vs. PMNS



Area ~V^2

Why these values? Are the two related? Are they related to masses?

Masses



12 orders of magnitude differences not explained; t quark as heavy as Tungsten

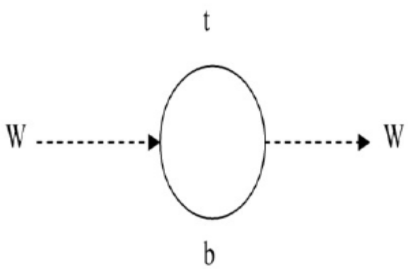
Theorists task

- A given theoretical model must explain all the data

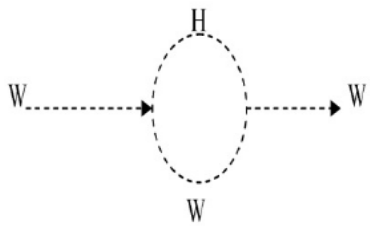
Model must thread through all experimental constraints (12 axe handles). One measurement can, in principle, defeat the theorist, but we seek a consistent pattern.

Flavor Physics as a NP discovery tool

- While measurements of CKM parameters & masses are fun, the main purpose of Flavor Physics is to find and/or define the properties of physics beyond the SM
- FP probes large mass scales via virtual quantum loops. An example, of the importance of such loops are changes in the W mass
  - M_w changes due to m_t $\quad \frac{dM_W}{dm_t} \alpha \frac{m_t}{M_w}$

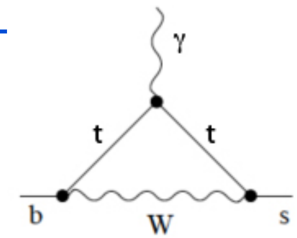


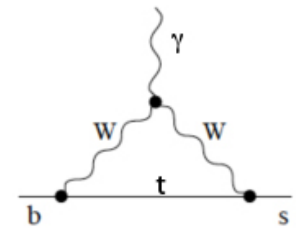
  - M_w changes due to m_H $\quad \frac{dM_W}{dm_H} \alpha - \frac{dm_H}{M_H}$

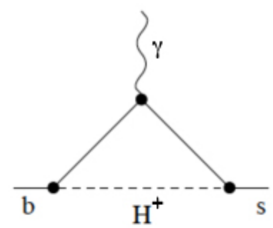


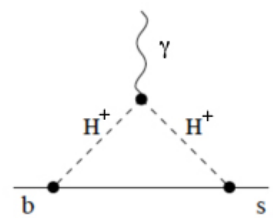
Ex. of Strong Constraints on NP

- Inclusive b→sγ, (Eγ > 1.6 GeV)
  - Measured $(3.37\pm0.23)\times10^{-4}$
  - Theory $(3.15\pm0.23)\times10^{-4}$ (NNLL) Misiak arXiv:1010.4896
  - Ratio = 1.07±0.10, Limits most NP models
  - Example 2HDM
    $m(H^+) > 385$ GeV

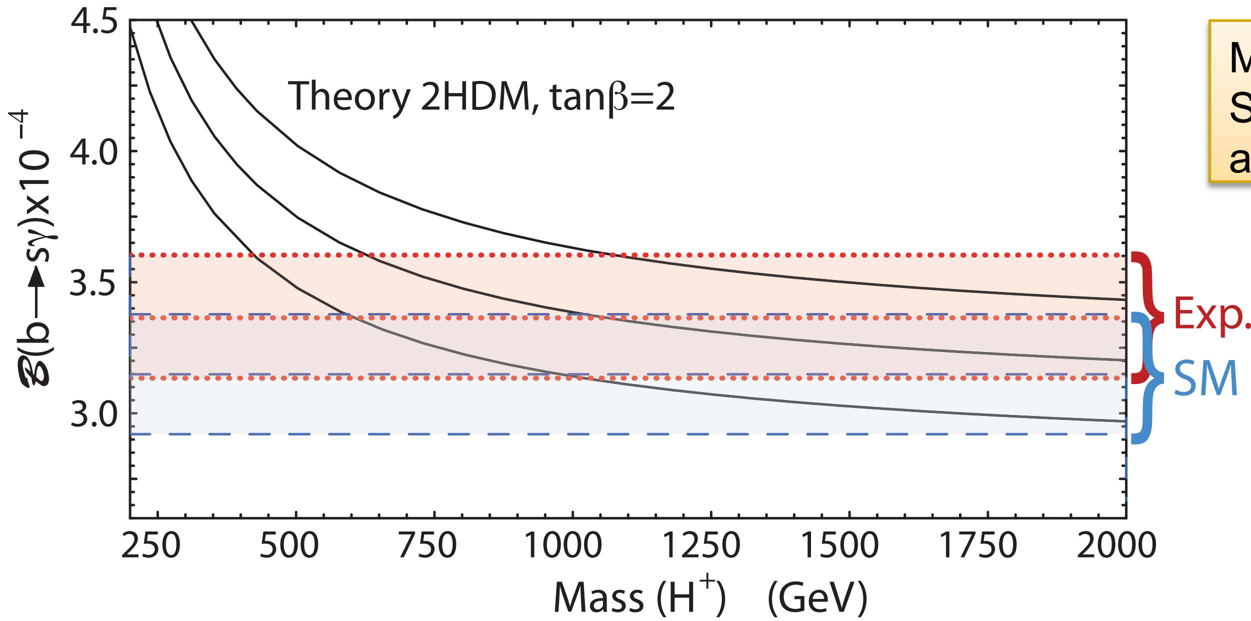








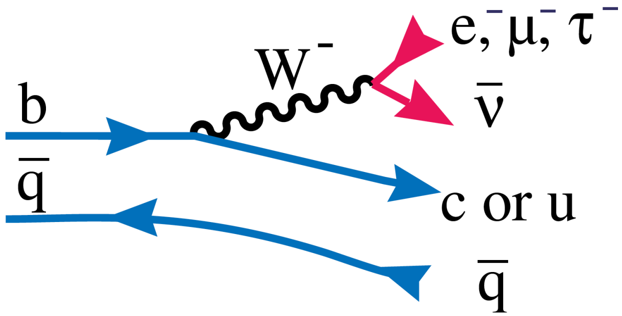
New BaBar
$(3.31\pm0.35)\times10^{-4}$
See G. Eigen's
ICHEP talk



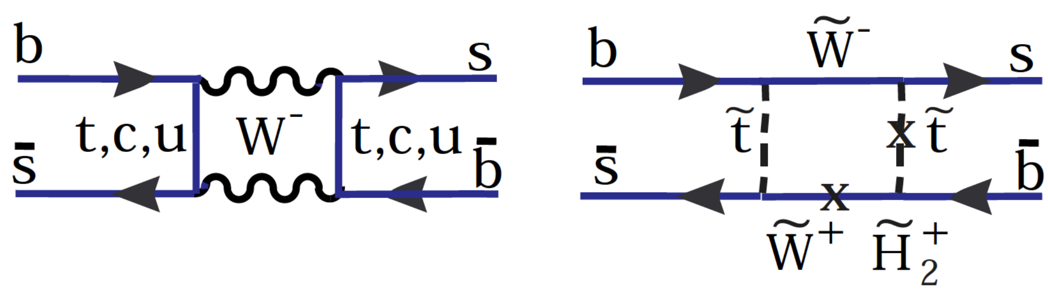
Misiak et. al hep-ph/0609232,
See also A. Buras et. al,
arXiv:1105.5146

Limits on New Physics

- It is oft said that we have not seen New Physics, yet what we observe is the sum of Standard Model + New Physics. How to set limits on NP?
- One hypothesis: assume that tree level diagrams are dominated by SM and loop diagrams could contain NP



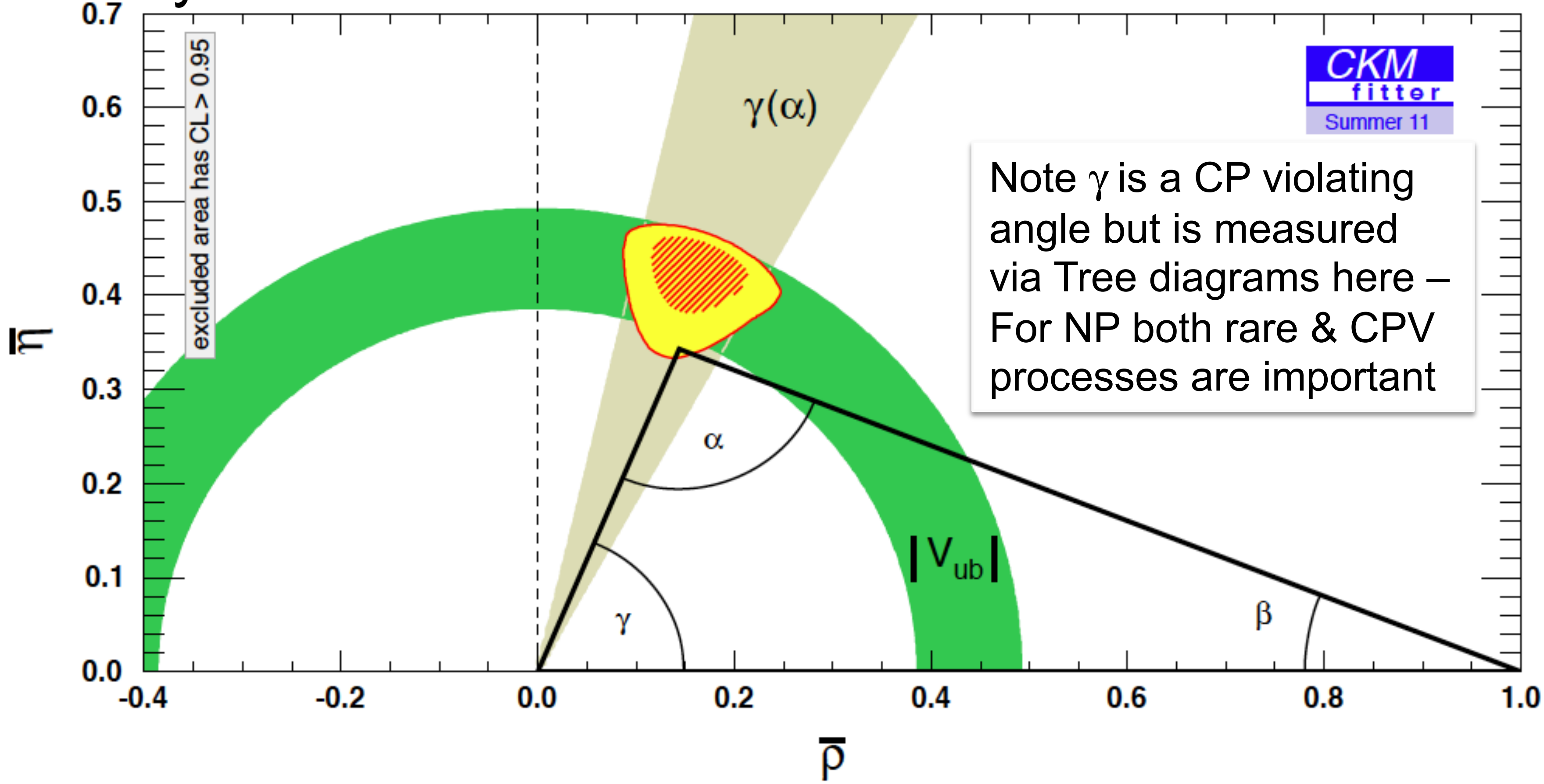
Tree diagram example



Loop diagram example

What are limits on NP from quark decays?

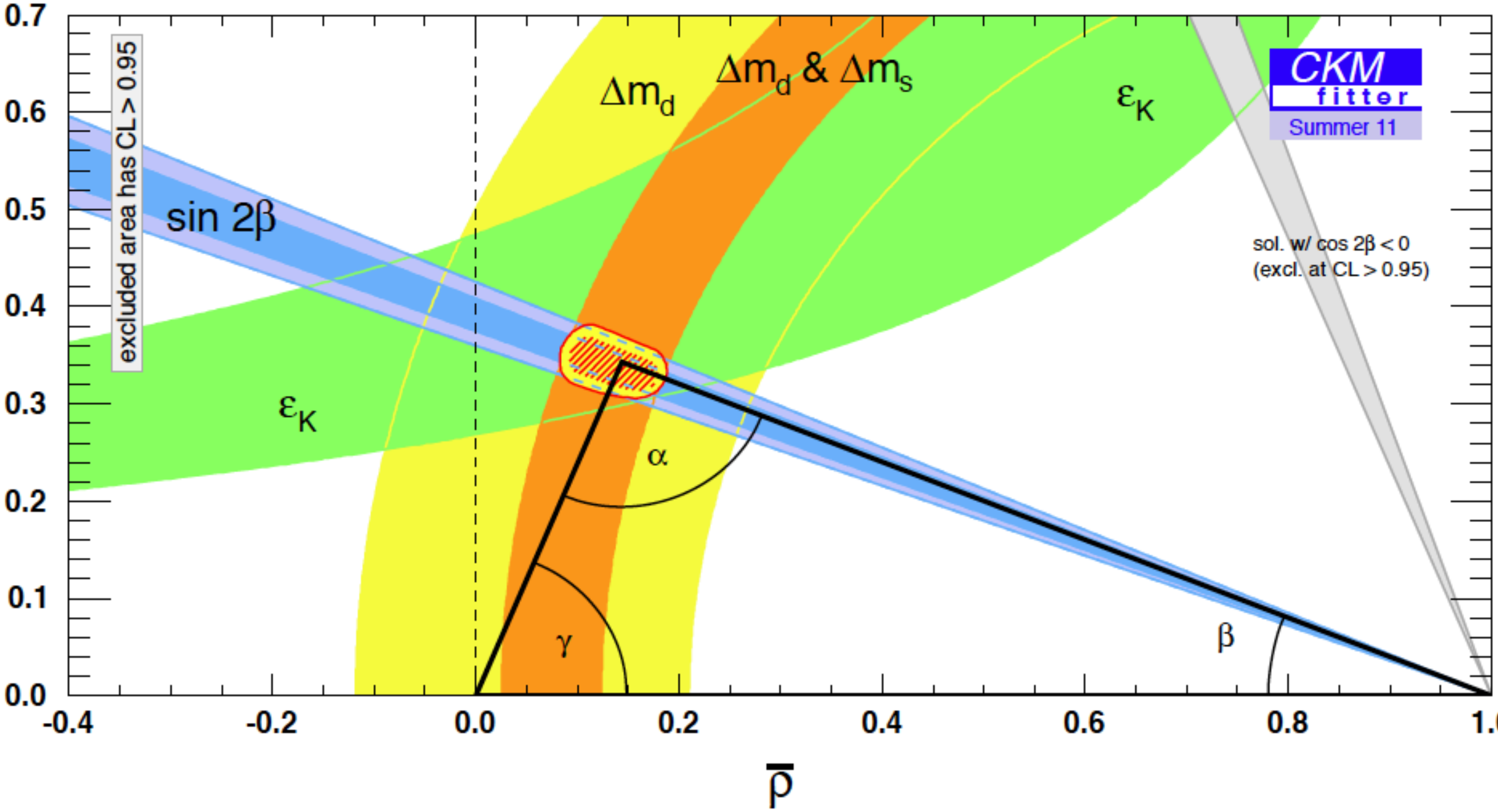
- Tree diagrams are unlikely to be affected by physics beyond the Standard Model



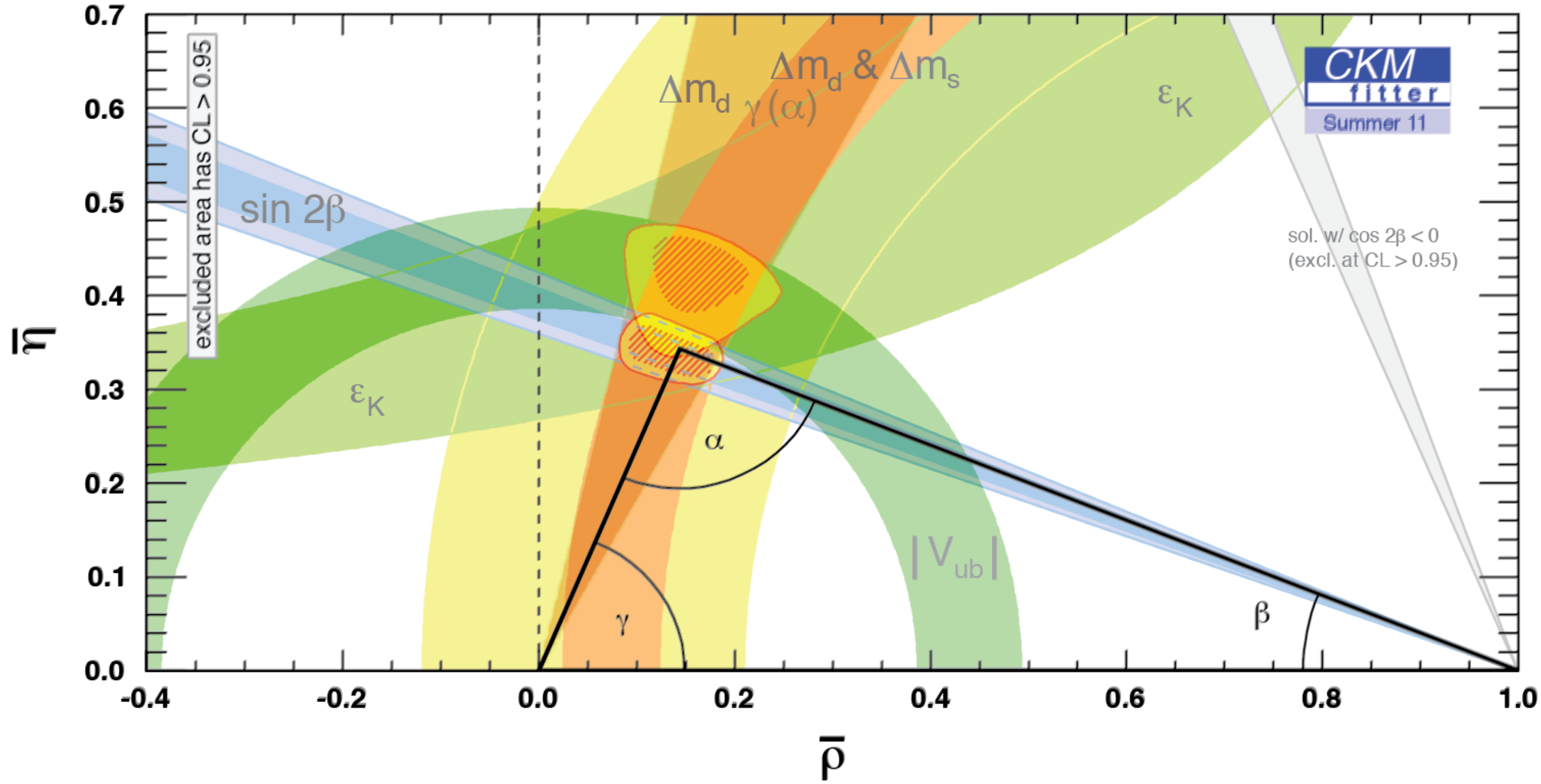
Note γ is a CP violating angle but is measured via Tree diagrams here – For NP both rare & CPV processes are important

CP Violation in B° & K° Only

- Absorptive (Imaginary) part of mixing diagram should be sensitive to New Physics. Lets compare



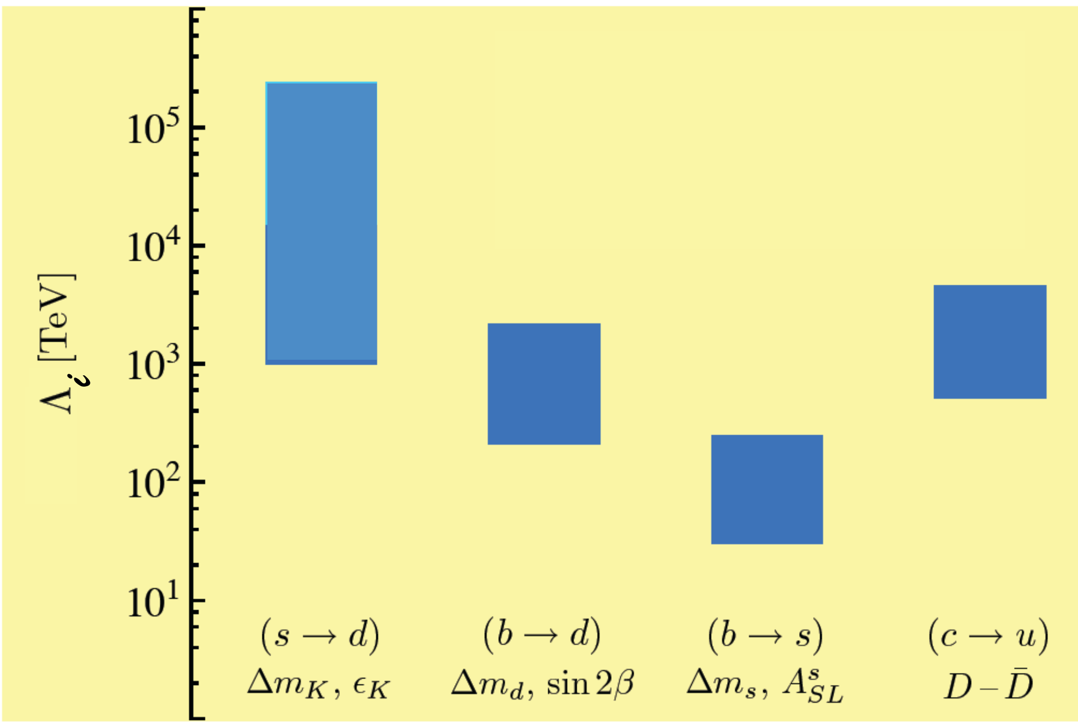
They are Consistent



- But consistency is only at the 5% level
- Limits on NP can be derived from difference

Flavor as a High Mass Probe

- Already excluded ranges from box diagrams
  - $\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{c_i}{\Lambda_i^2} O_i$, take c_i ~1



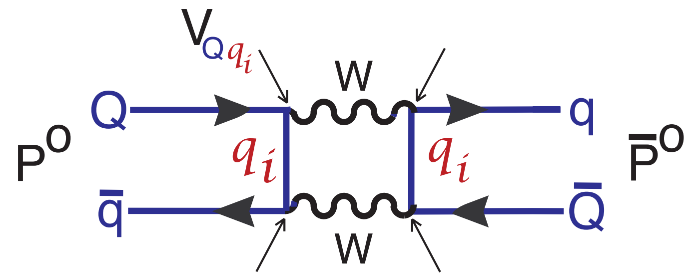
Ways out

1. New particles have large masses >>1 TeV
2. New particles have degenerate masses
3. Mixing angles in new sector are small, same as in SM (MFV)
4. The above already implies strong constrains on NP

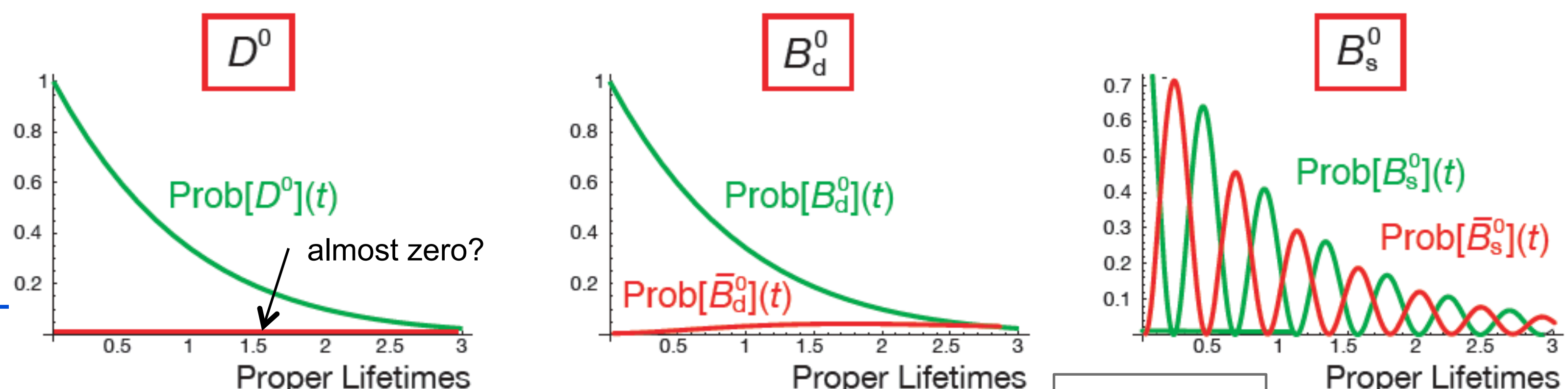
See: Isidori, Nir & Perez arXiv:1002.0900; Neubert EPS 2011 talk

Neutral Meson Mixing

- Neutral mesons can transform into their anti-particles via 2nd order weak interactions
- Short distance transition rate depends on
  - mass of intermediate q_i, the heavier the larger, favors s & b since t is allowed
  - CKM elements V_{ij}



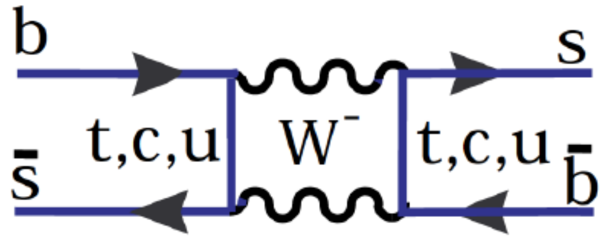
New particles possible in the loop



from Van Kooten

Mixing &CPV Definitions

- Mixing & Decay:



$$i\frac{d}{dt}\begin{pmatrix} B_s^0 \\ \overline{B}_s^0 \end{pmatrix} = \begin{pmatrix} M_{11} - \Gamma_{11}/2 & M_{12} - i\Gamma_{12}/2 \\ M_{12}^* - i\Gamma_{12}^*/2 & M_{22} - i\Gamma_{22}/2 \end{pmatrix}\begin{pmatrix} B_s^0 \\ \overline{B}_s^0 \end{pmatrix}$$

- $|M_L\rangle = p|M^o\rangle + q|\overline{M}^o\rangle$, $|M_H\rangle = p|M^o\rangle - q|\overline{M}^o\rangle$,
- $mB_s = (M_H + M_L)/2$, $\Delta M = M_H - M_L$,
  $1/\tau_{Bs} = \Gamma = (\Gamma_H + \Gamma_L)/2$, $\Delta\Gamma = \Gamma_L - \Gamma_H$,
- $y \equiv \Delta\Gamma / 2\Gamma$

CPV Time Evolution

- Consider $a[f(t)] = \frac{\Gamma(\bar{M} \to f) - \Gamma(M \to f)}{\Gamma(\bar{M} \to f) + \Gamma(M \to f)}$ where *f* is a CP eigenstate
- Define $A_f \equiv A(M \to f), \bar{A}_f \equiv A(\bar{M} \to f), \quad \lambda_f = \frac{p}{q}\frac{\bar{A}_f}{A_f}$
- λ_f is a function of V_{ij} in SM

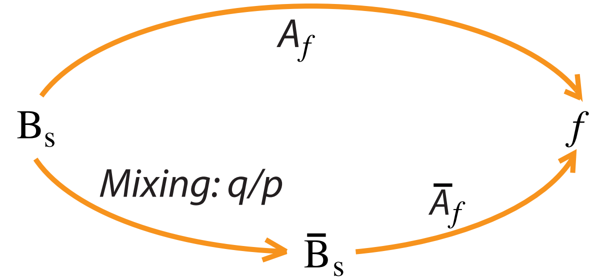
$$\Gamma(M \to f) = N_f \left|A_f\right|^2 e^{-\Gamma t}\left(\cosh\frac{\Delta\Gamma t}{2} - \mathrm{Re}\,\lambda_f \sinh\frac{\Delta\Gamma t}{2} - \mathrm{Im}\,\lambda_f \sin(\Delta M t)\right)$$

$$\Gamma(\bar{M} \to f) = N_f \left|A_f\right|^2 e^{-\Gamma t}\left(\cosh\frac{\Delta\Gamma t}{2} - \mathrm{Re}\,\lambda_f \sinh\frac{\Delta\Gamma t}{2} + \mathrm{Im}\,\lambda_f \sin(\Delta M t)\right)$$

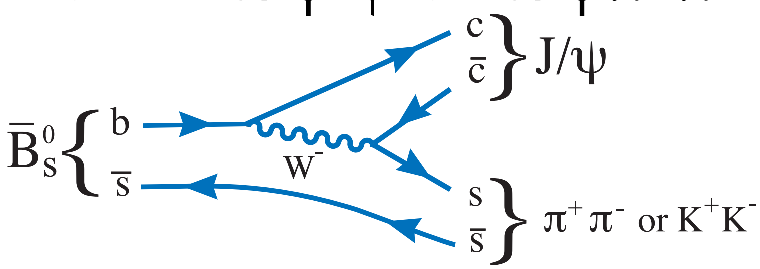
See Nierste
arXiv:0904.1869 [hep-ph]

CPV in $B_s \to J/\psi X$

- Interference between mixing & decay



- For f =$J/\psi\ \phi$ or $J/\psi\pi^+\pi^-$

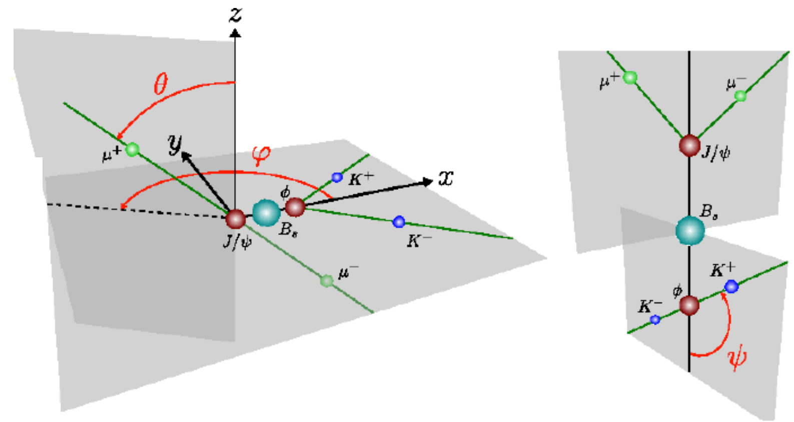


$$\varphi_s^{SM} \equiv -2\beta_s = -2\arg\left(-\frac{V_{ts}V^*_{tb}}{V_{cs}V^*_{cb}}\right) = -0.04 \text{ rad}$$

- Small CPV expected, good place for NP to appear
- $B_s \to J/\psi\phi$ is not a CP eigenstate, as it's a vector-vector final state, so must do an angular analysis to separate the CP+ and CP- components

J/ψϕ: Transversity

$$\frac{d^4\Gamma(B_s^0 \to J/\psi\phi)}{dt\ d\cos\theta\ d\varphi\ d\cos\psi} \equiv \frac{d^4\Gamma}{dt\ d\Omega} \propto \sum_{k=1}^{10} h_k(t) f_k(\Omega)$$



k	$h_k(t)$	$f_k(\theta,\psi,\varphi)$
1	$\lvert A_0\rvert^2(t)$	$2\cos^2\psi\,(1-\sin^2\theta\cos^2\phi)$
2	$\lvert A_\parallel(t)\rvert^2$	$\sin^2\psi\,(1-\sin^2\theta\sin^2\phi)$
3	$\lvert A_\perp(t)\rvert^2$	$\sin^2\psi\sin^2\theta$
4	$\Im(A_\parallel(t)\,A_\perp(t))$	$-\sin^2\psi\sin 2\theta\sin\phi$
5	$\Re(A_0(t)\,A_\parallel(t))$	$\frac{1}{2}\sqrt{2}\,\sin 2\psi\sin^2\theta\sin 2\phi$
6	$\Im(A_0(t)\,A_\perp(t))$	$\frac{1}{2}\sqrt{2}\,\sin 2\psi\sin 2\theta\cos\phi$
7	$\lvert A_s(t)\rvert^2$	$\frac{2}{3}(1-\sin^2\theta\cos^2\phi)$
8	$\Re(A_s^*(t)A_\parallel(t))$	$\frac{1}{3}\sqrt{6}\sin\psi\sin^2\theta\sin 2\phi$
9	$\Im(A_s^*(t)A_\perp(t))$	$\frac{1}{3}\sqrt{6}\sin\psi\sin 2\theta\cos\phi$
10	$\Re(A_s^*(t)A_0(t))$	$\frac{4}{3}\sqrt{3}\cos\psi(1-\sin^2\theta\cos^2\phi)$

for S-wave under ϕ predicted by Stone & Zhang PRD 79, 074024 (2009)

Transversity II

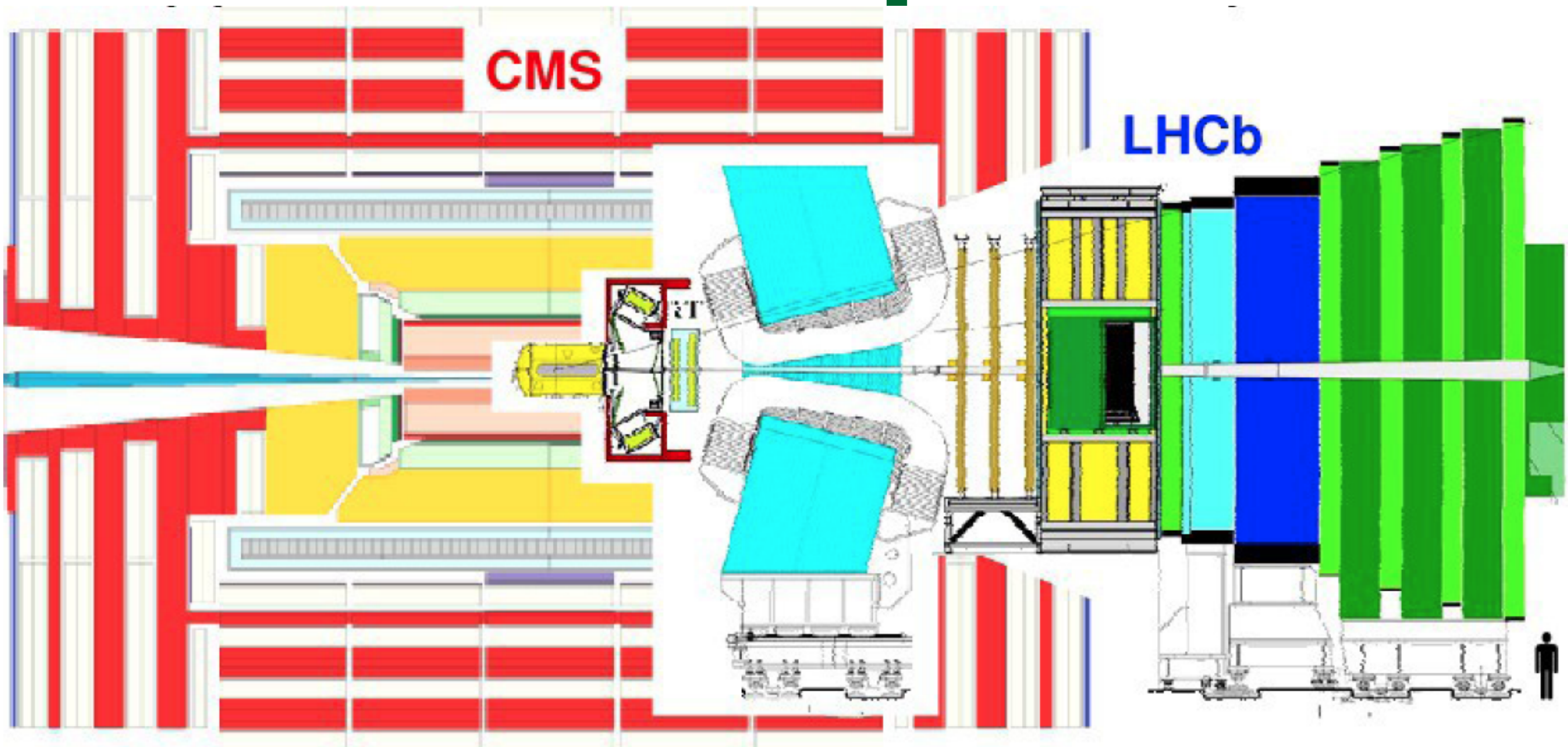
$$
\begin{aligned}
|A_0|^2(t) &= |A_0|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) + \sin\phi_s \sin(\Delta m t)\right], \\
|A_\parallel(t)|^2 &= |A_\parallel|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) + \sin\phi_s \sin(\Delta m t)\right], \\
|A_\perp(t)|^2 &= |A_\perp|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin\phi_s \sin(\Delta m t)\right], \\
\Im(A_\parallel^*(t)\, A_\perp(t)) &= |A_\parallel||A_\perp| e^{-\Gamma_s t}\left[-\cos(\delta_\perp - \delta_\parallel) \sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right)\right. \\
&\quad \left. - \cos(\delta_\perp - \delta\_\|) \cos\phi_s \sin(\Delta m t) + \sin(\delta_\perp - \delta_\parallel)\cos(\Delta m t)\right], \\
\Re(A_0^*(t)\, A_\parallel(t)) &= |A_0||A_\parallel| e^{-\Gamma_s t} \cos(\delta_\parallel - \delta_0)\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right)\right. \\
&\quad \left. + \sin\phi_s \sin(\Delta m t)\right], \\
\Im(A_0^*(t)\, A_\perp(t)) &= |A_0||A_\perp| e^{-\Gamma_s t}\left[-\cos(\delta_\perp - \delta_0) \sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right)\right. \\
&\quad \left. - \cos(\delta_\perp - \delta_0) \cos\phi_s \sin(\Delta m t) + \sin(\delta_\perp - \delta_0)\cos(\Delta m t)\right], \\
|A_s(t)|^2 &= |A_s|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin\phi_s \sin(\Delta m t\right], \\
\Re(A_s^*(t) A_\parallel(t)) &= |A_s||A_\parallel| e^{-\Gamma_s t}\left[-\sin(\delta_\parallel - \delta_s) \sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin(\delta_\parallel - \delta_s)\ \cos\phi_s \sin(\Delta m t)\right. \\
&\quad \left. + \cos(\delta_\parallel - \delta_s)\cos(\Delta m t)\right], \\
\Im(A_s^*(t) A_\perp(t)) &= |A_s||A_\perp| e^{-\Gamma_s t} \sin(\delta_\perp - \delta_s)\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right)\right. \\
&\quad \left. - \sin\phi_s \sin(\Delta m t)\right], \\
\Re(A_s^*(t) A_0(t)) &= |A_s||A_0| e^{-\Gamma_s t}\left[-\sin(\delta_0 - \delta_s) \sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right)\right. \\
&\quad \left. - \sin(\delta_0 - \delta_s) \cos\phi_s \sin(\Delta m t) + \cos(\delta_0 - \delta_s)\cos(\Delta m t)\right].
\end{aligned}
$$

only term for $f=f_{cp}$

Time Dependent CPV in B_s decay

- For B^o ΔM=0.507 ps^{-1}
- For B_s ΔM_s= 17.77 ps^{-1}
- ∴ excellent decay time resolution is required, large B_s production is also necessary
- Province of hadron collider experiments
- Hints from CDF & D0 for new physics
- New more precise results from LHCb

LHCb experiment

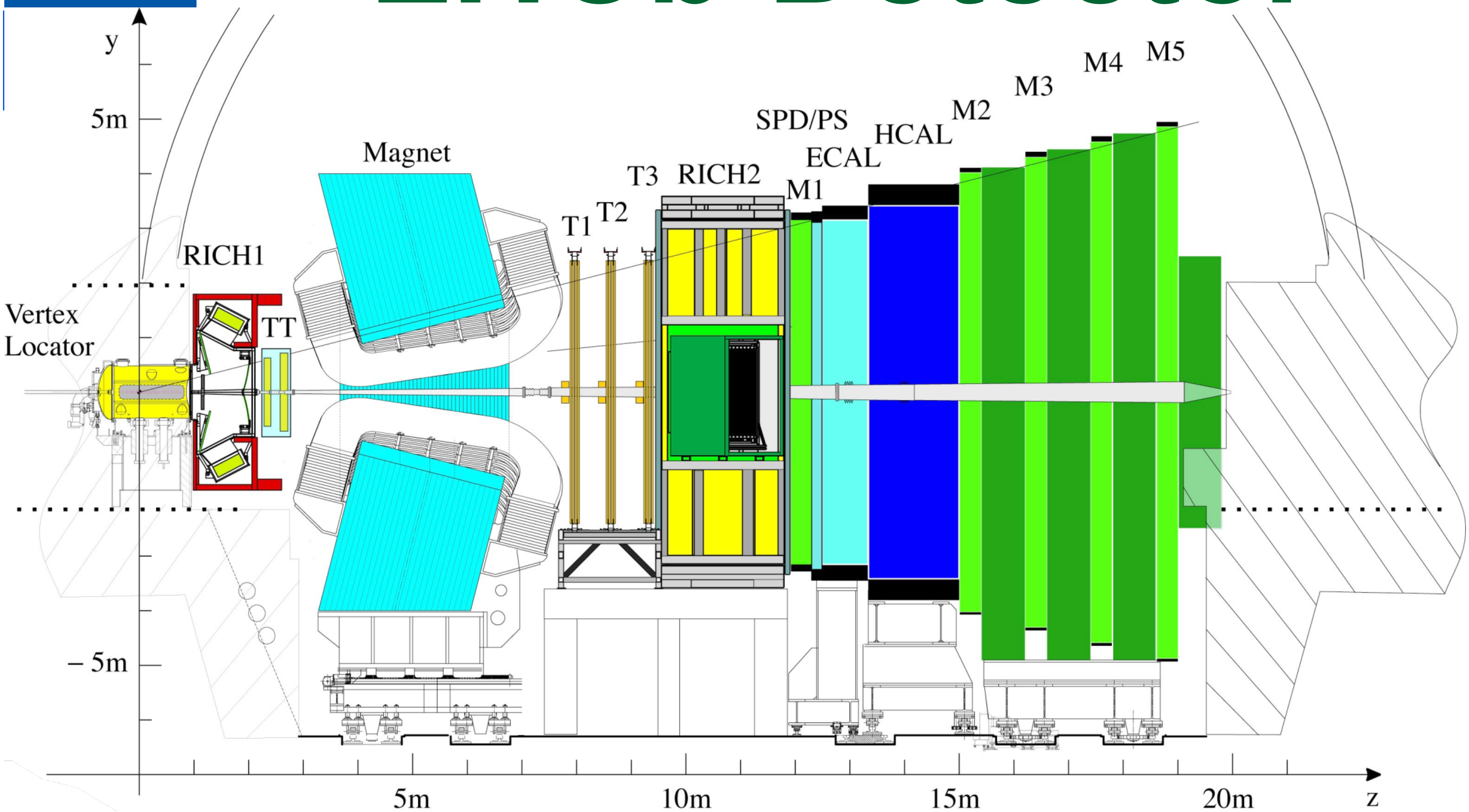


The LHCb Collaboration

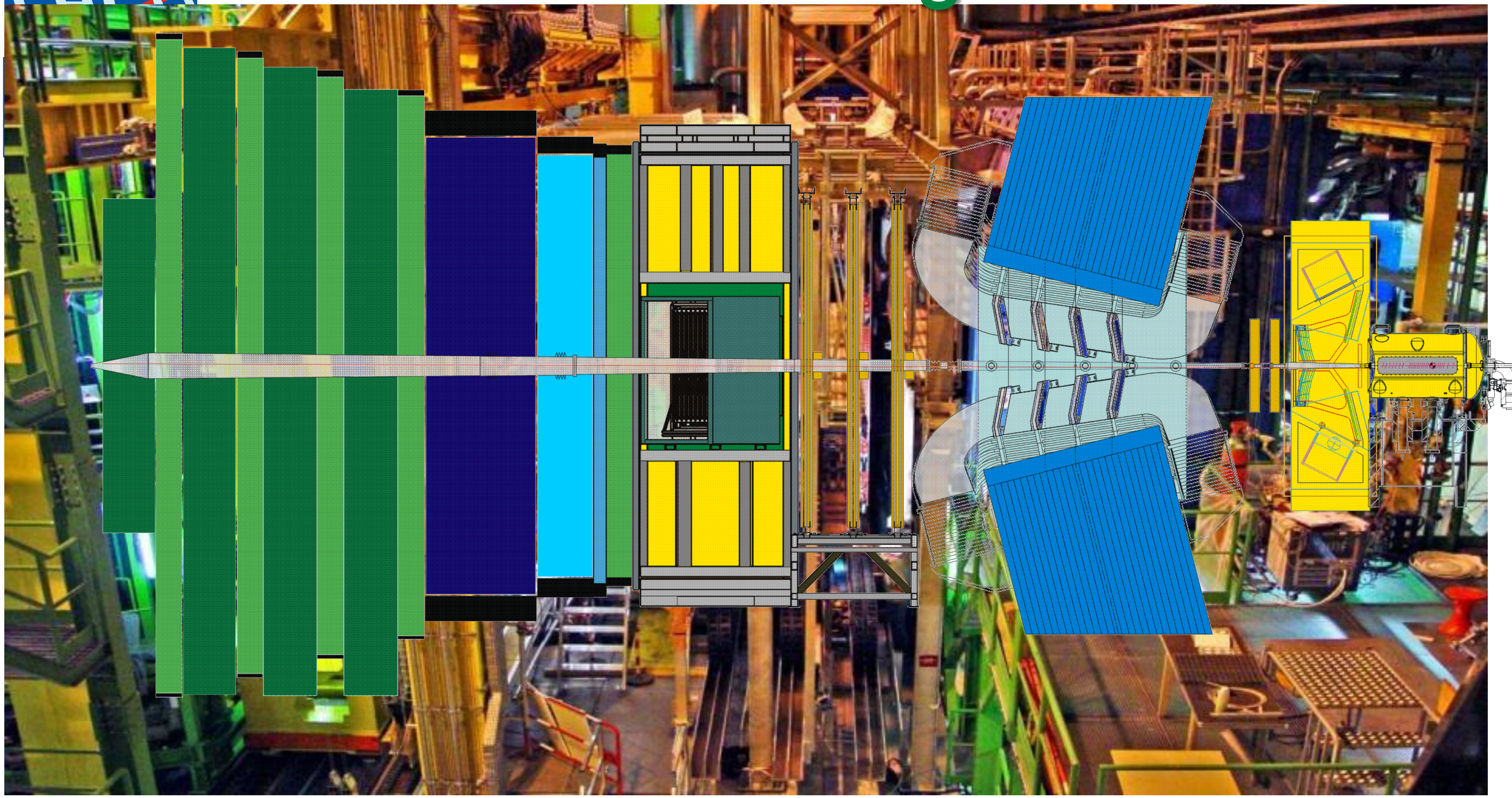
- 800 Physicists
- 54 Institutes
- 15 Countries
  - 3 Groups from USA

- Basking in light of 2008 Nobel Prize to Kobayshi & Maskawa, "for the discovery of the origin of the broken symmetry which predicts the existence of at least 3 families of quarks"

LHCb Detector

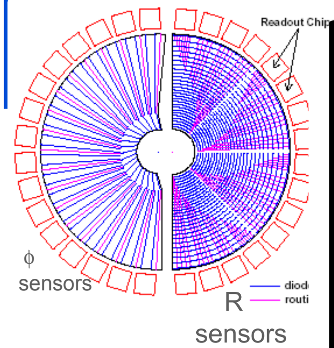


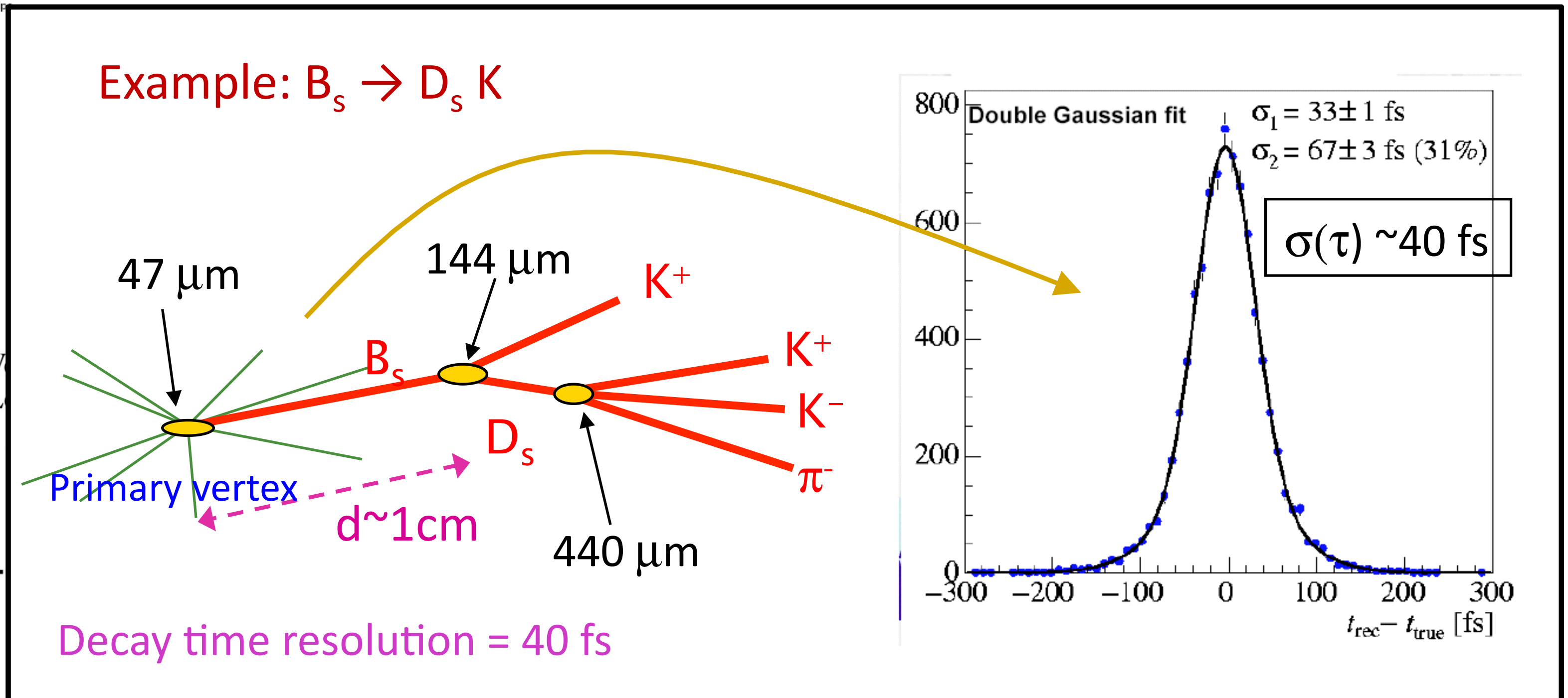
Detector Workings

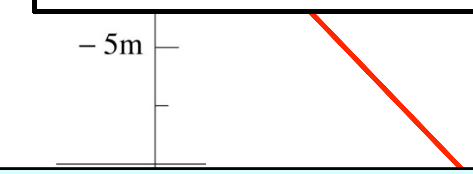


LHCb detector ~ fully installed and commissioned → walk through the detector using the example of a $B_s \rightarrow D_s K$ decay

B-Vertex Measurement





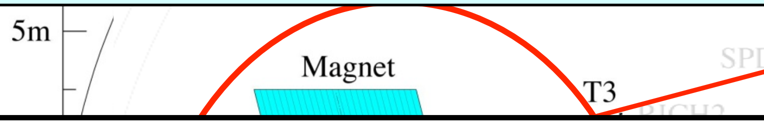


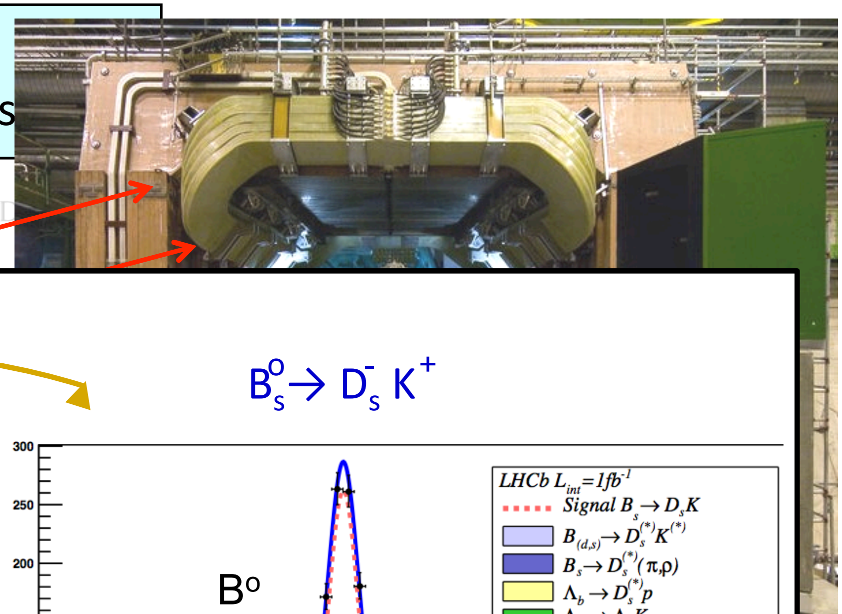
Vertex Locator (Velo)
Silicon strip detector with
~ 5 μm hit resolution
→ 30 μm IP resolution

Vertexing:
- trigger on impact parameter
- measurement of decay distance (time)

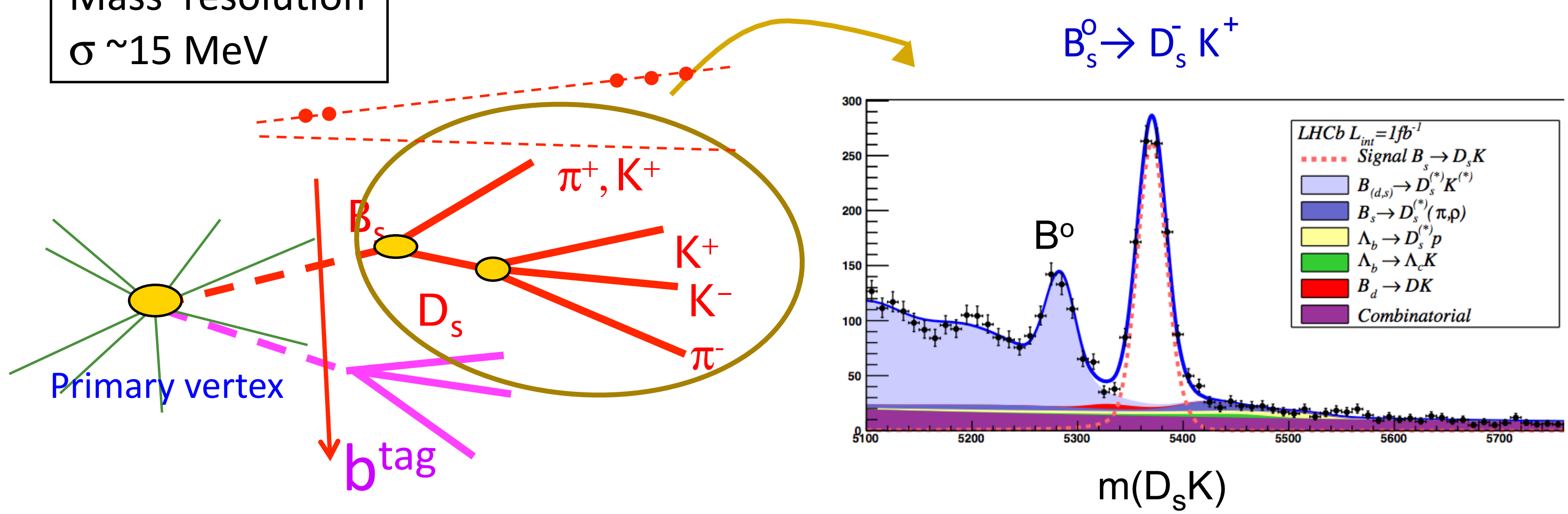
Momentum and Mass measurement

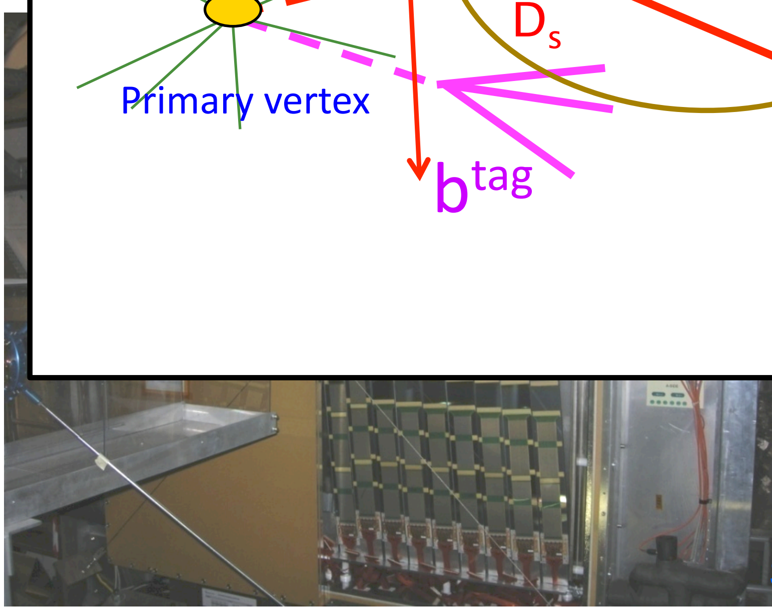
Momentum meas. + direction (VELO):
Mass resolution for background suppres

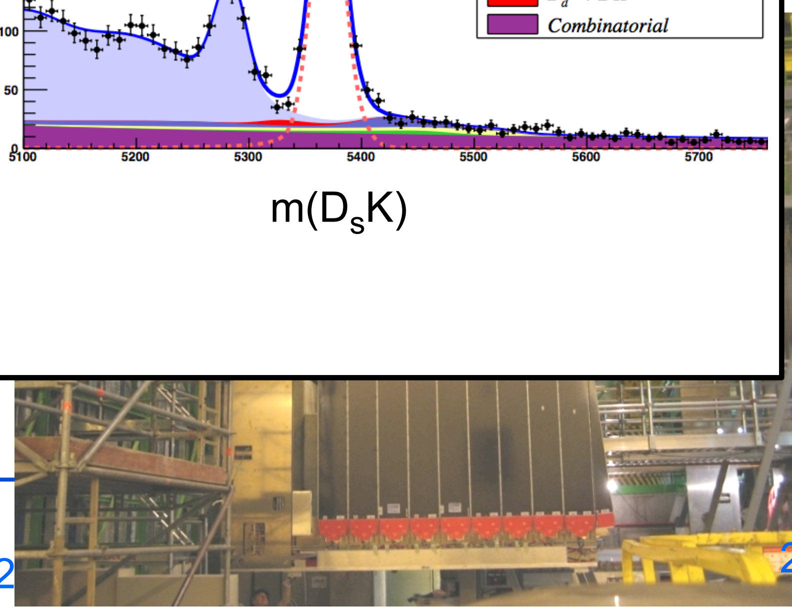




Mass resolution
σ ~15 MeV

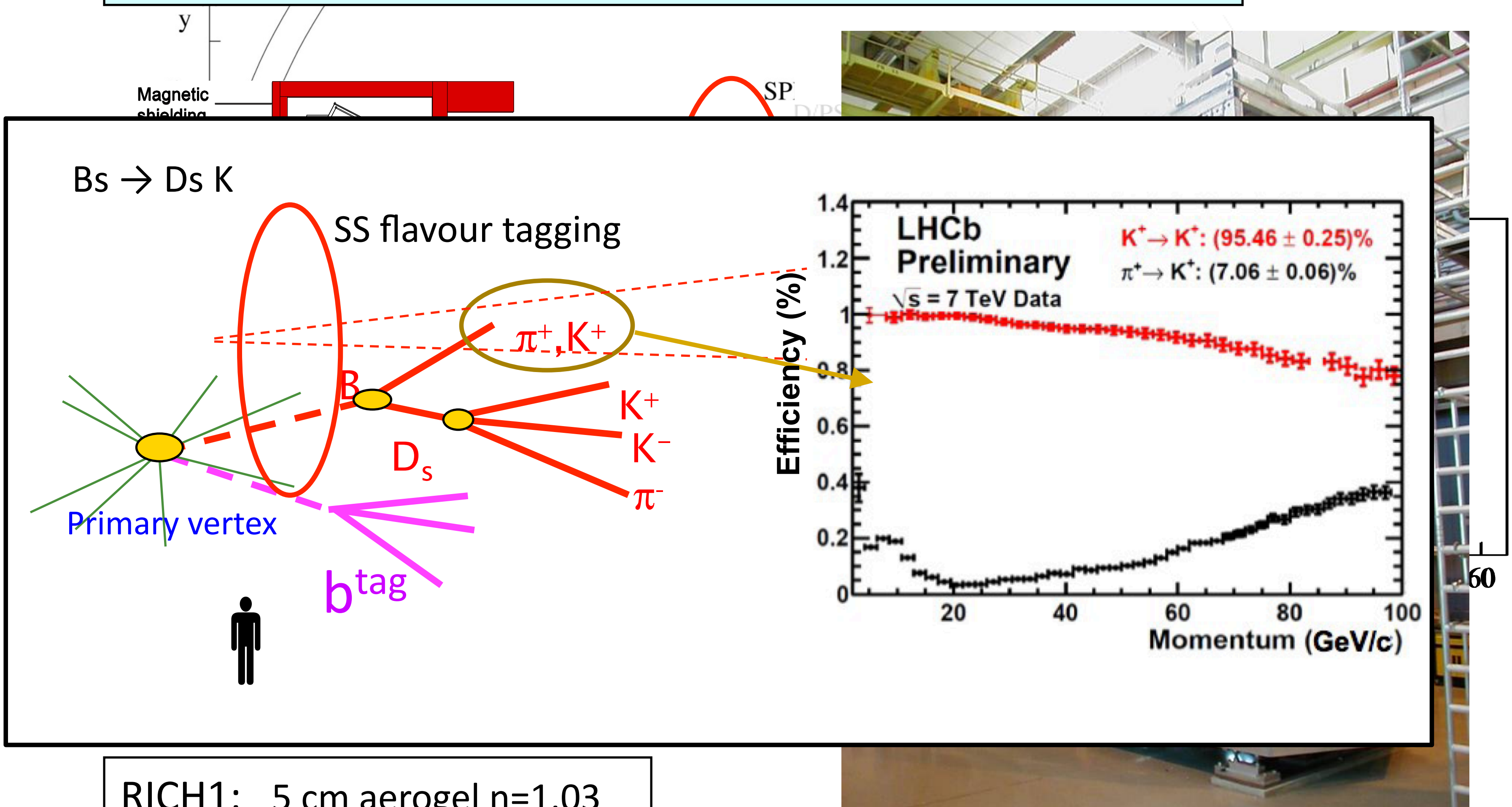






Hadron Identification

RICH: K/π identification using Cherenkov light emission angle

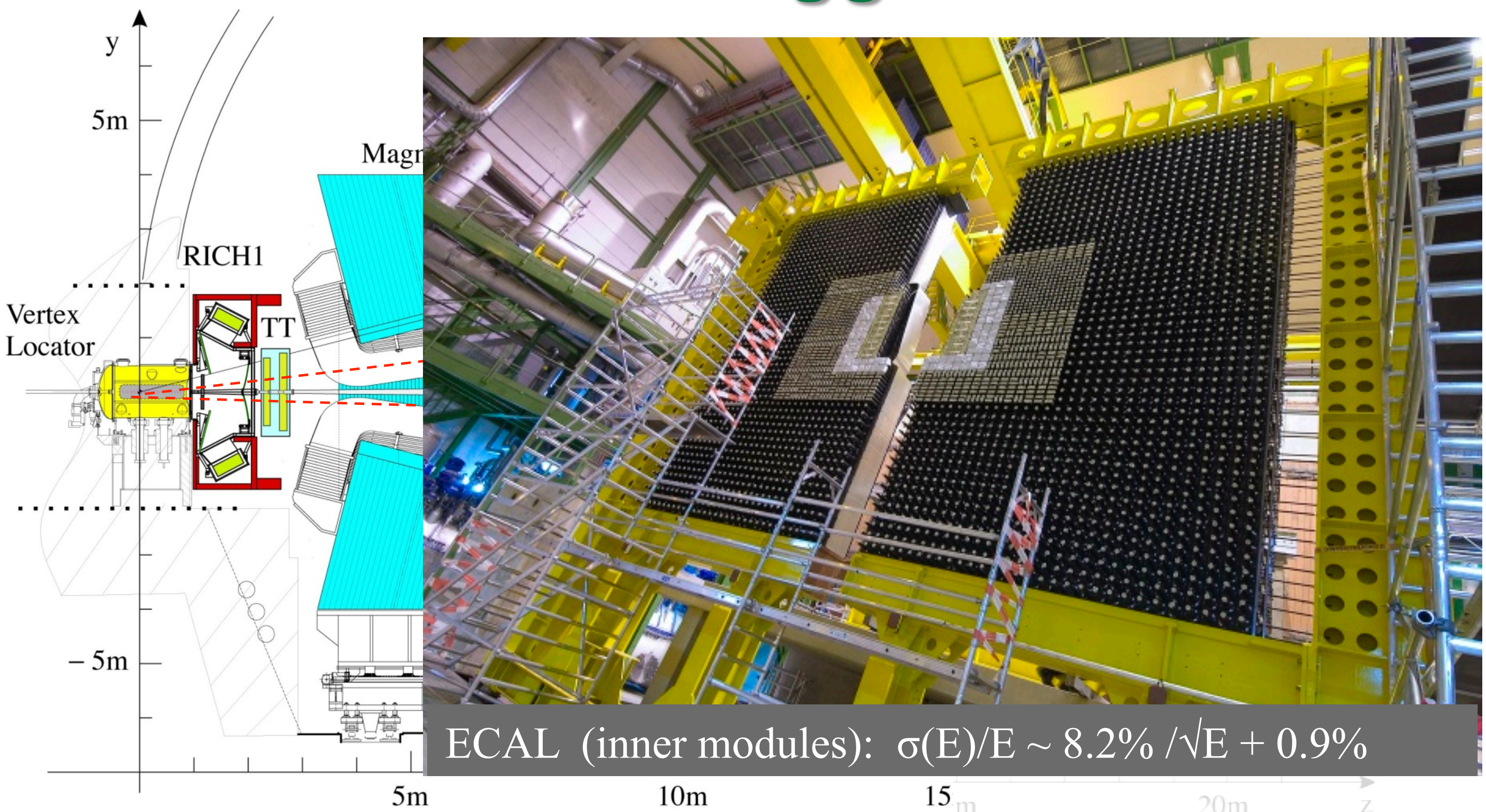


RICH1: 5 cm aerogel n=1.03

$4\ m^3\ C_4F_{10}$ n=1.0014

RICH2: $100\ m3\ CF_4$ n=1.0005

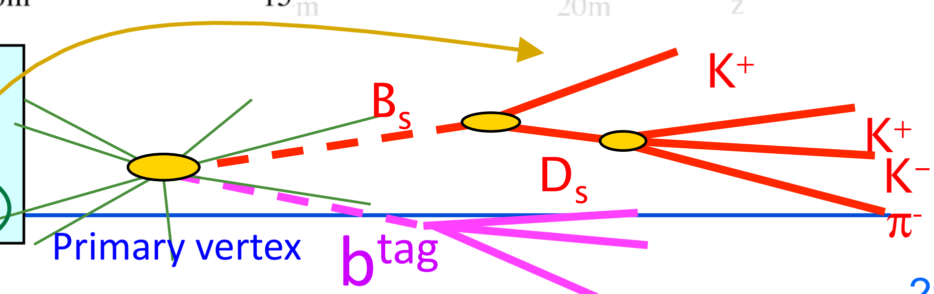
Particle identification and L0 trigger



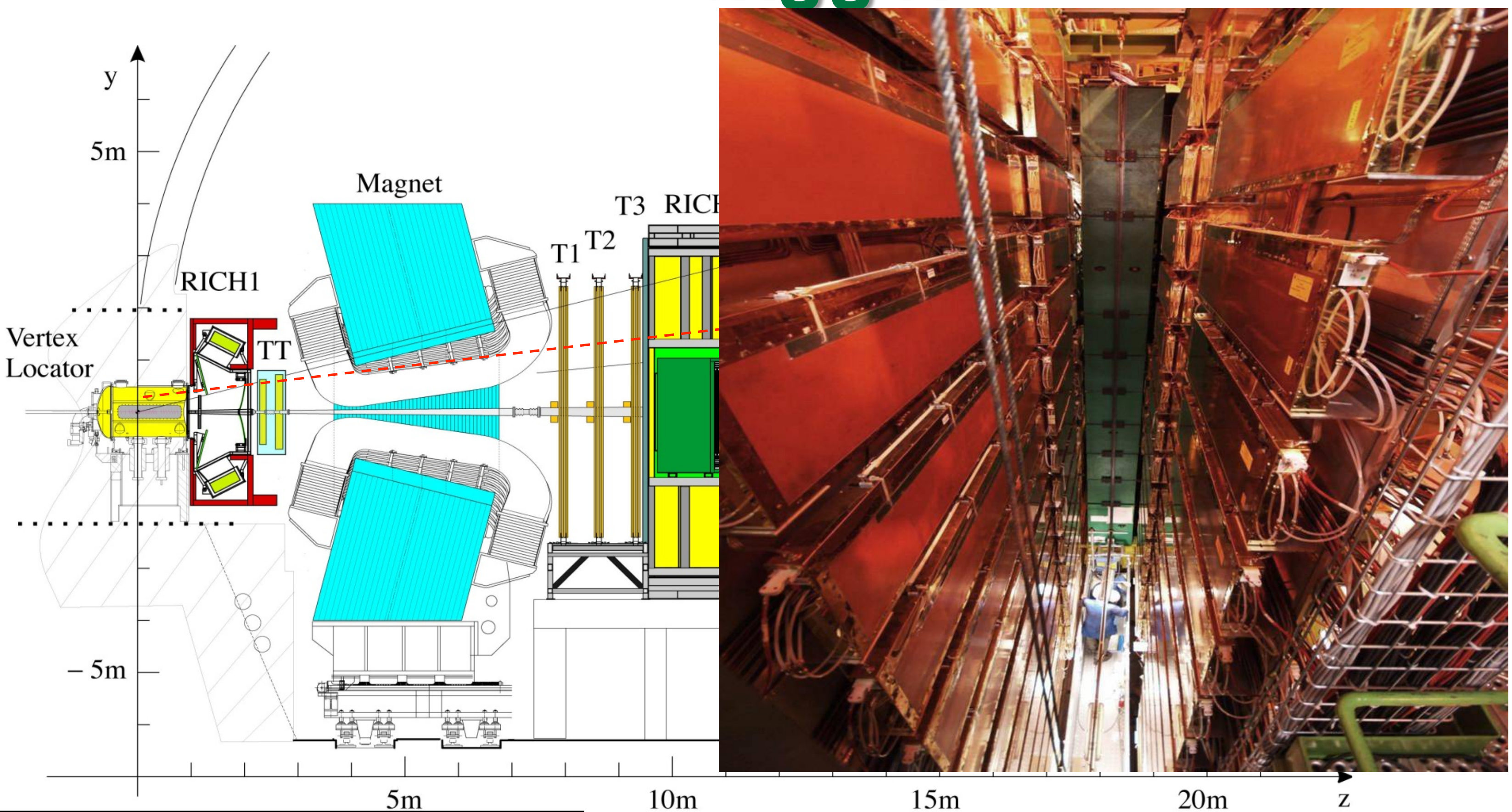
ECAL (inner modules): $\sigma(E)/E \sim 8.2\% /\sqrt{E} + 0.9\%$

Calorimeter system :

- Identify electrons, hadrons, π^0 ,γ
- Level 0 trigger: high E_T electron and hadron

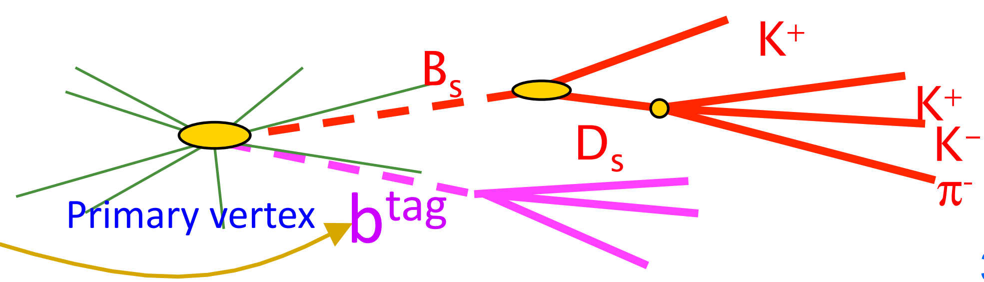


Particle identification and L0 trigger

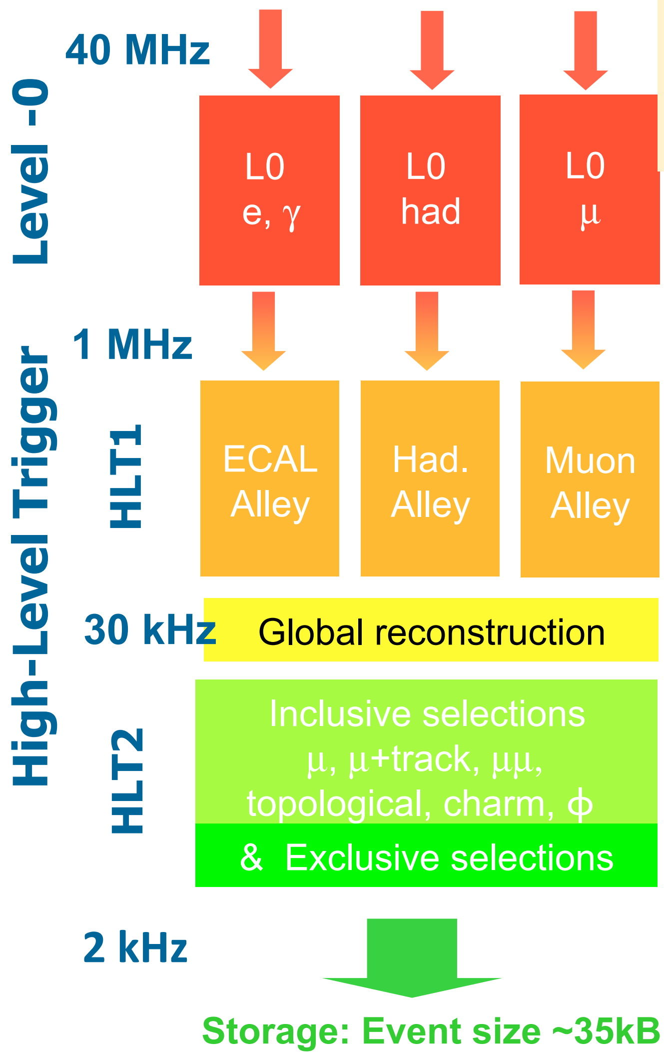


Muon system:

- Level 0 trigger: High P_t muons
- OS flavour tagging



Triggering



Trigger is crucial as $\sigma_{b\bar{b}}$ is less than 1% of total inelastic cross section and B decays of interest typically have $\mathcal{B} < 10^{-5}$

- **Hardware level (L0)**

  Search for high-p_T μ, e, γ and hadron candidates

- **Software level (High Level Trigger, HLT)**

  Farm with $\mathcal{O}$(2000) multi-core processors

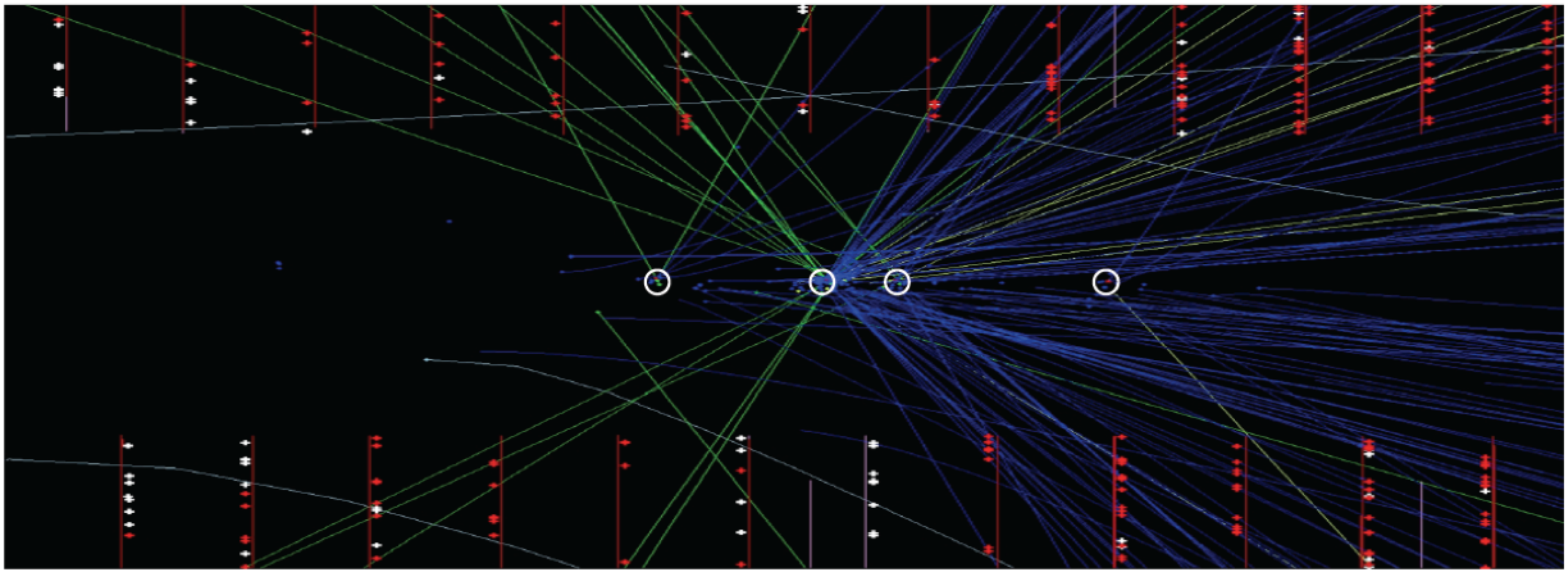
  HLT1: Confirm L0 candidate with more complete info, add impact parameter and lifetime cuts

  HLT2: B reconstruction + selections

	ε(L0)	ε(HLT1)	ε(HLT2)
Electromagnetic	70 %		
Hadronic	50 %	> ~80 %	> ~90 %
Muon	90 %		

Running Conditions

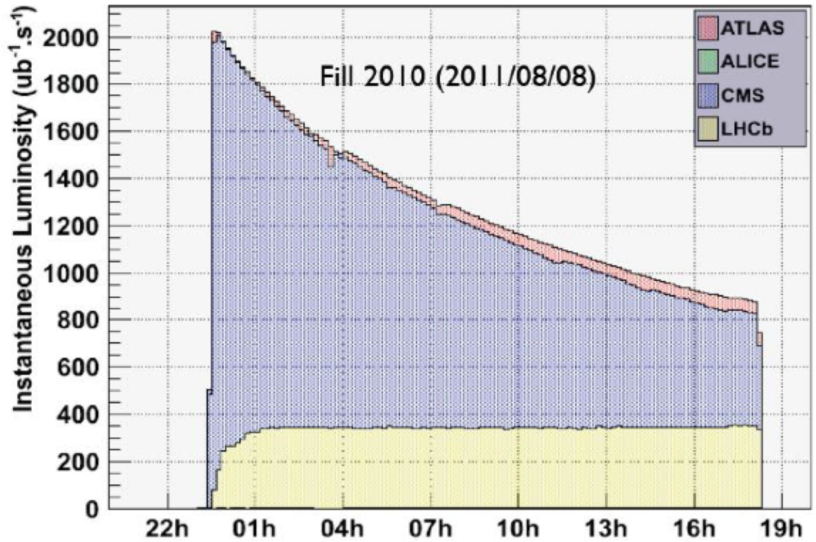
VELO rz view

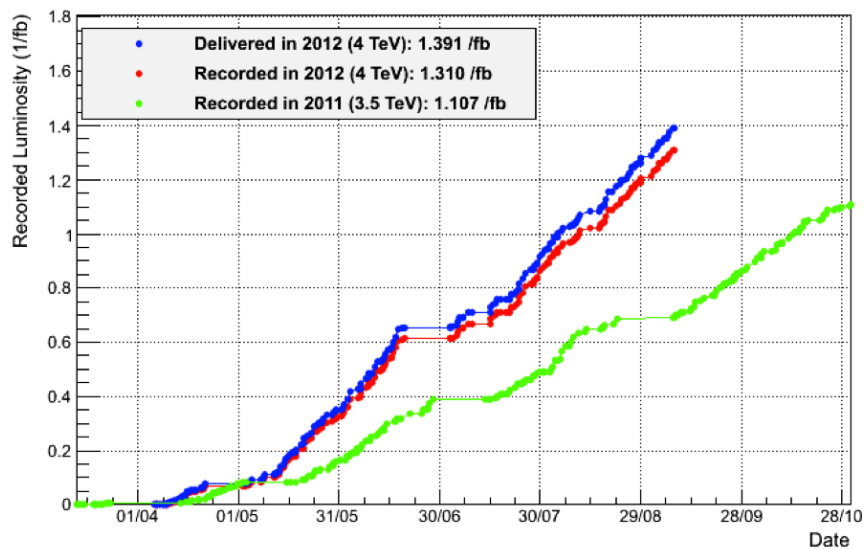


- 20 MHz of bunch crossing (in 2012, with 50 ns bunch spacing) with an average of 2 p-p interactions per bunch crossing → this level of pileup not an issue for LHCb

Luminosity Leveling

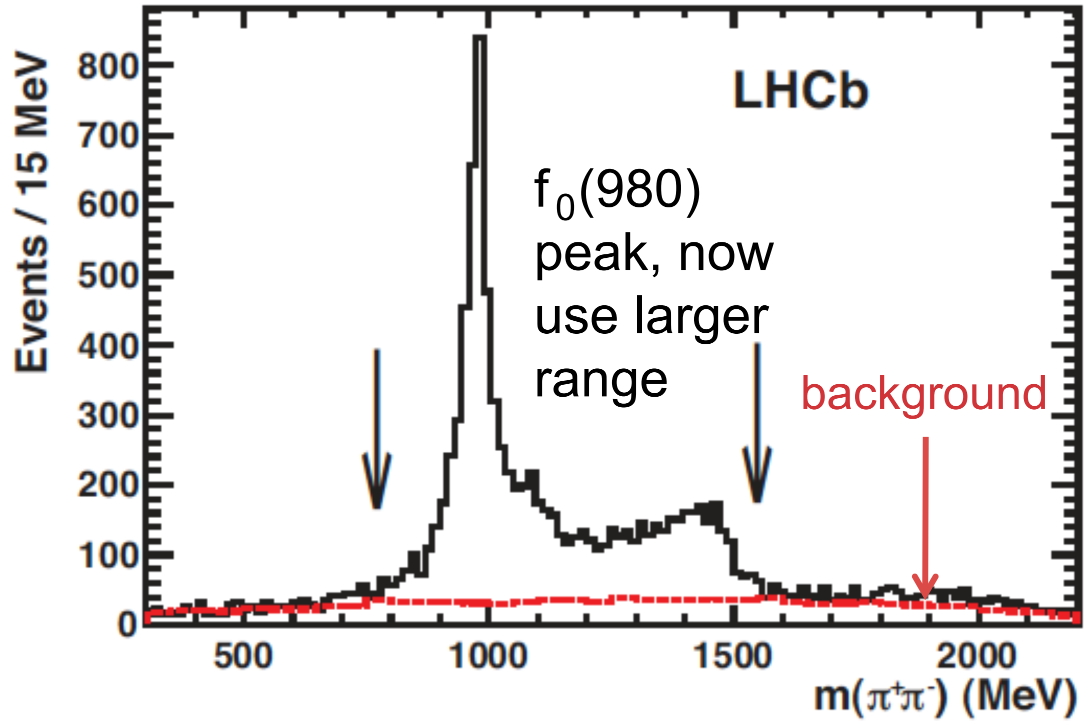
- Luminosity is maintained as at a constant value of ~4x10^{32}/cm·s by displacing beams transversely
- Integral $\mathcal{L}$ is 1/fb in 2011, expect 2.2/fb more in 2012





ϕ_s from $B_s \rightarrow J/\psi\pi^+\pi^-$

- Reconstructed $\pi^+\pi^-$ mass spectrum
- In region between arrows, measured to be >97.7% CP-odd @95% cl
- $a[f(t)] \sim 2\sin\phi_s \sin(\Delta M t)$
- $\phi_s = -0.019^{+0.173+0.004}_{-0.174-0.003}$ rad



ϕ_s results from $J/\psi\phi$

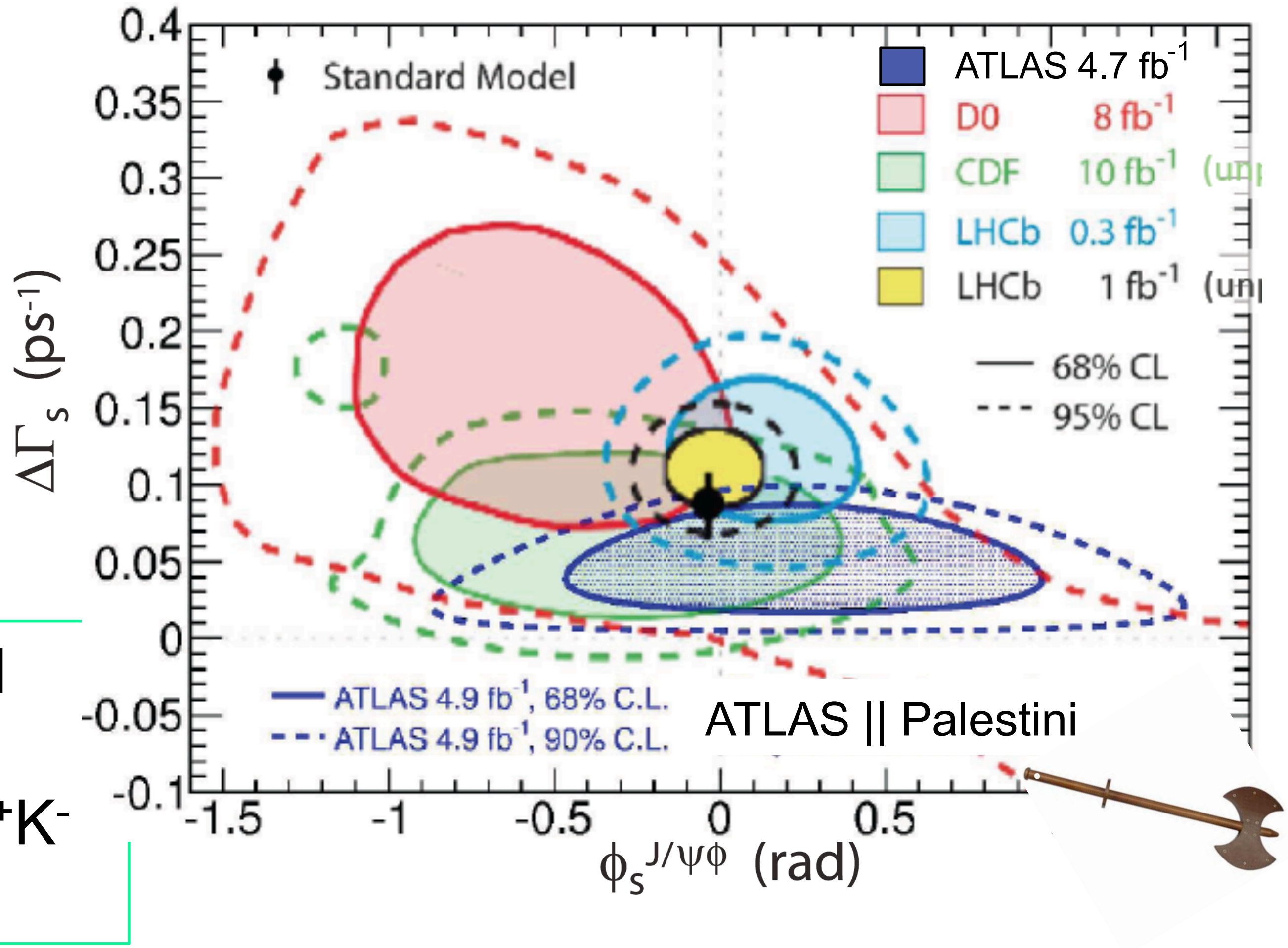
LHCb values

$\Gamma = 0.6580 \pm 0.0054 \pm 0.0066\,(\text{ps}^{-1})$

$\Delta\Gamma = 0.116 \pm 0.018 \pm 0.006\,(\text{ps}^{-1})$

$\phi_s = 0.001 \pm 0.101 \pm 0.027\,(\text{rad})$

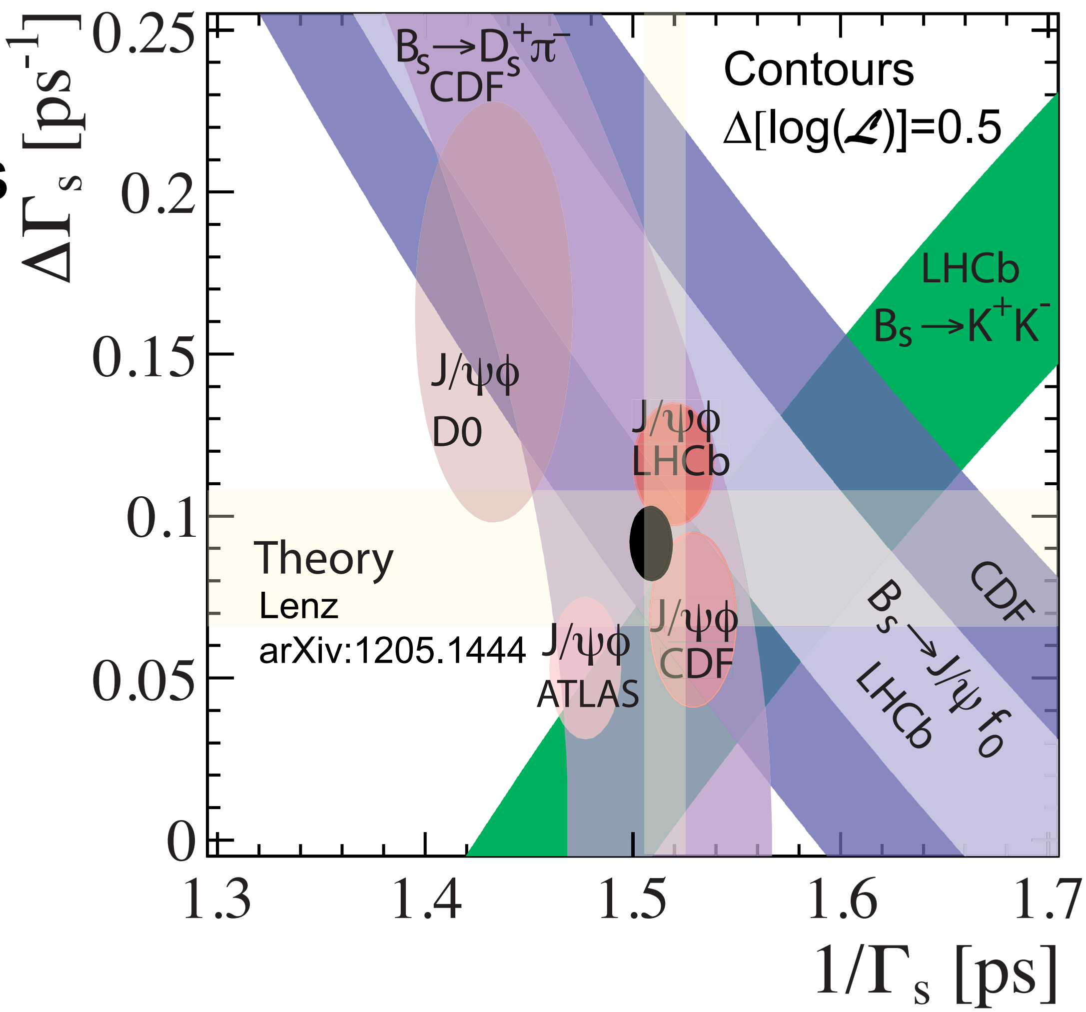
Ambiguity removed using interference with K^+K^- S-wave



- Combining LHCb results: $\phi_s = -0.002 \pm 0.083 \pm 0.027$ rad

Γ_s & $\Delta\Gamma_s$

- B_s lifetime results here use only fully reconstructed decays
- K^+K^- is taken as CP even ($A_{\Delta\Gamma}$=-1)
- Ovals show 39% cl, while bands 68% cl
- τ_s=1.509±0.010 ps, $\Delta\Gamma_s$ = 0.092±0.011 ps^{-1}, $y_s=\Delta\Gamma_s/2\Gamma_s$= 0.07±0.01 (from Anna Phan)



only full reconstructed B_s decays used

a_{sl}

- By definition $$a_{sl} = \frac{\Gamma(\bar{M} \to f) - \Gamma(M \to \bar{f})}{\Gamma(\bar{M} \to f) + \Gamma(M \to \bar{f})}$$

  at t=0 $\bar{M} \to f$ is zero as is $M \to \bar{f}$
- Here *f* is by construction flavor specific, $f \neq \bar{f}$
- Can measure eg. $\bar{B}_s \to D_s^+ \mu^- \nu$, versus $B_s \to D_s^- \mu^+ \nu$,
- Or can consider that muons from two B decays can be like-sign when one mixes and the other decays, so look at $\mu^+\mu^+$ vs $\mu^-\mu^-$
- a_{sl} is expected to be very small in the SM, $a_{sl}=(\Delta\Gamma/\Delta M) \tan\phi_{12}$, where $\tan\phi_{12}=\mathrm{Arg}(-\Gamma_{12}/M_{12})$
- In SM (B^o) $a_{sl}^d = -4.1\times10^{-4}$, ($B_s$) $a_{sl}^s = +1.9\times10^{-5}$

arXiv:1205.1444 [hep-ph]

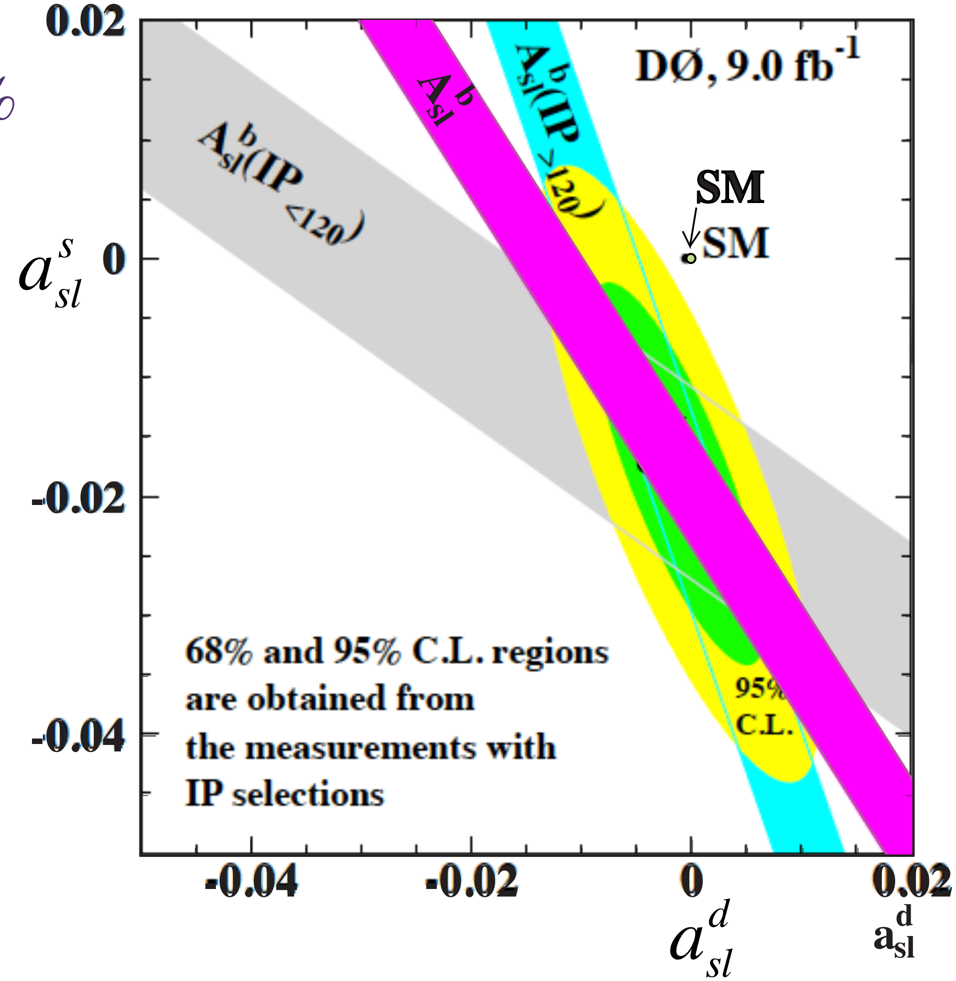
D0 a_{sl}

- Using dimuons (3.9σ)

$$A_{sl}^{b} = (-0.787 \pm 0.172 \pm 0.093)\%$$

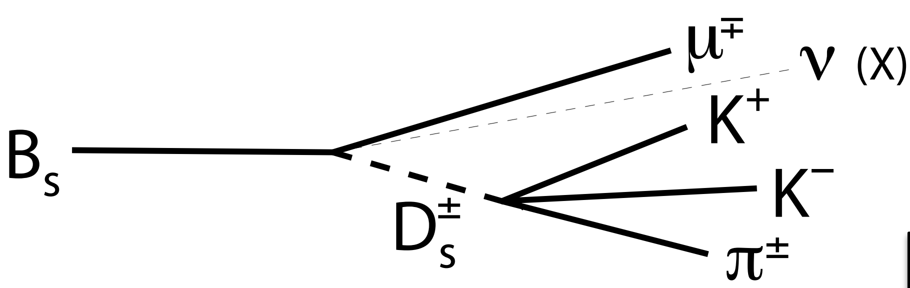
- Indication from D0 that its B_s
- Separate dimuons into B_d and B_s samples using muon impact parameter
- Find $a_{sl}^{d} = (-0.12 \pm 0.52)\%$

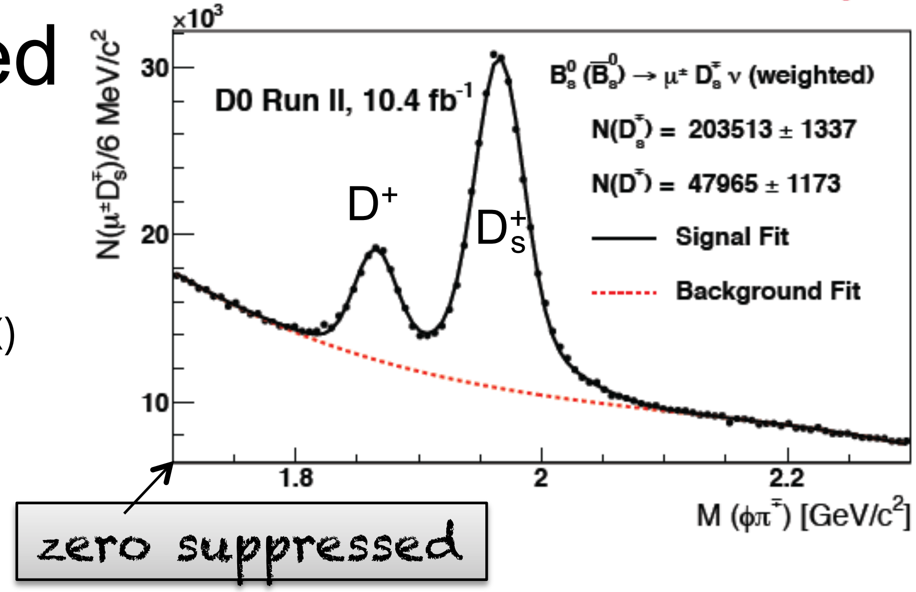
$$a_{sl}^{s} = (-1.81 \pm 1.06)\%$$



New D0 Analysis

- Measure a_{sl}^{s} using $D_s \mu^- \nu$ events, $D_s \to \phi\pi^{\pm}$
- Detect a μ associated with a D_s decay

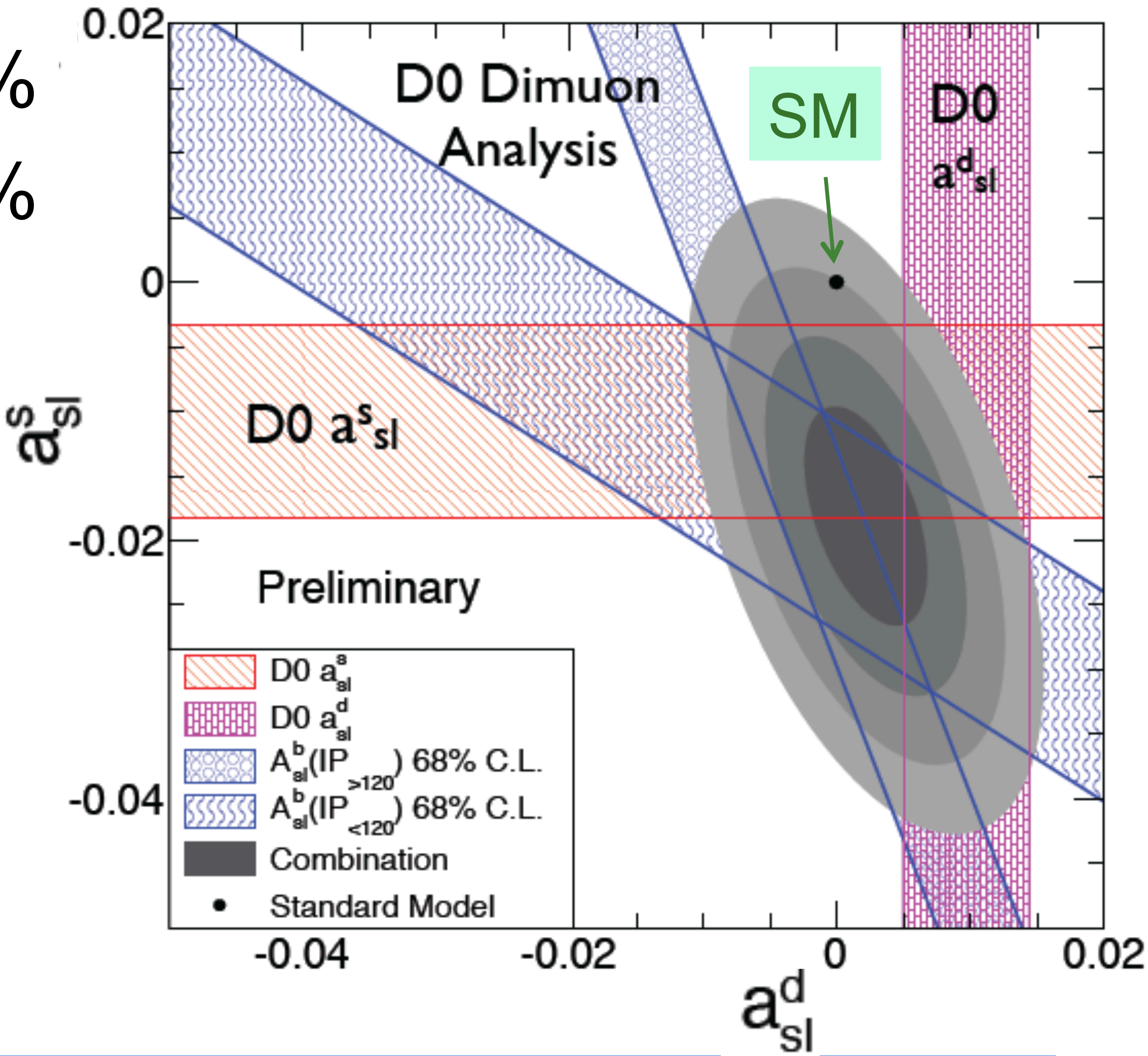




- Find a_{sl}^{s}=(-1.08±0.72±0.17)%
- Also measure a_{sl}^{d} using $D^+\mu^-\nu$, $D^+ \to K\pi^+\pi^+$
- a_{sl}^{d}=(0.93±0.45±0.14)%

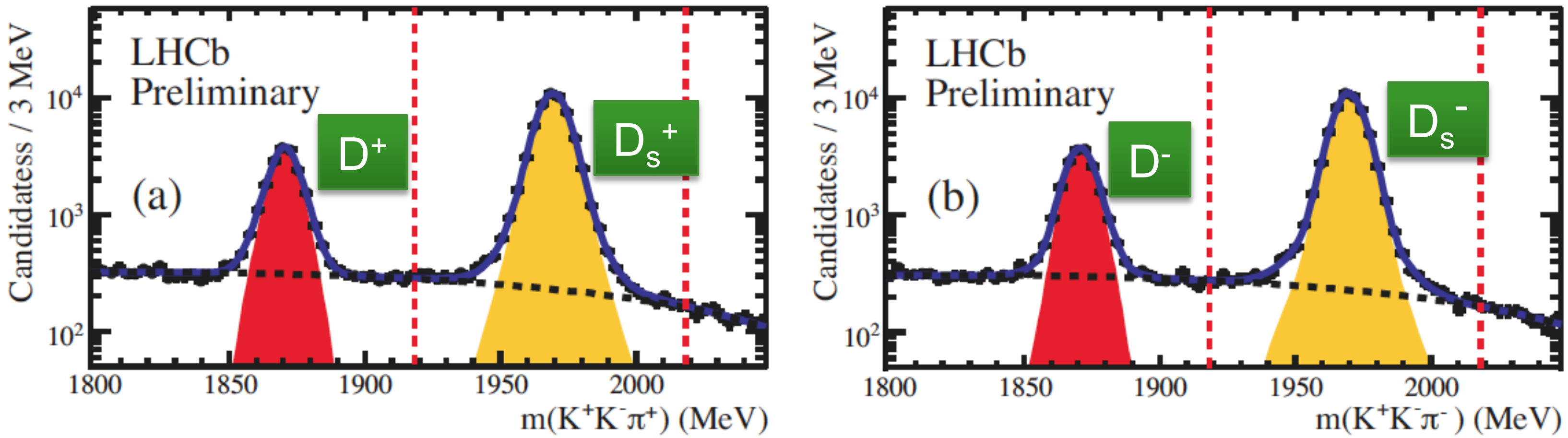
a_{sl} according to D0

- a_{sl}^{s}=(-1.81±0.56)%
- a_{sl}^{d}=(-0.22±0.30)%
- 3σ from SM
- arXiv:1208.5813



LHCb measurement

- Use $D_s \mu^- \nu$, $D_s \to \phi\pi^\pm$, magnet is periodicaly reversed. For magnet down:



- Effect of B_s production asymmetry is reduced to a negligible level by rapid mixing oscillations
- Calibration samples (J/ψ, D^{*+}) used to measure detector trigger, track & muon ID biases

a_{sl} not D0

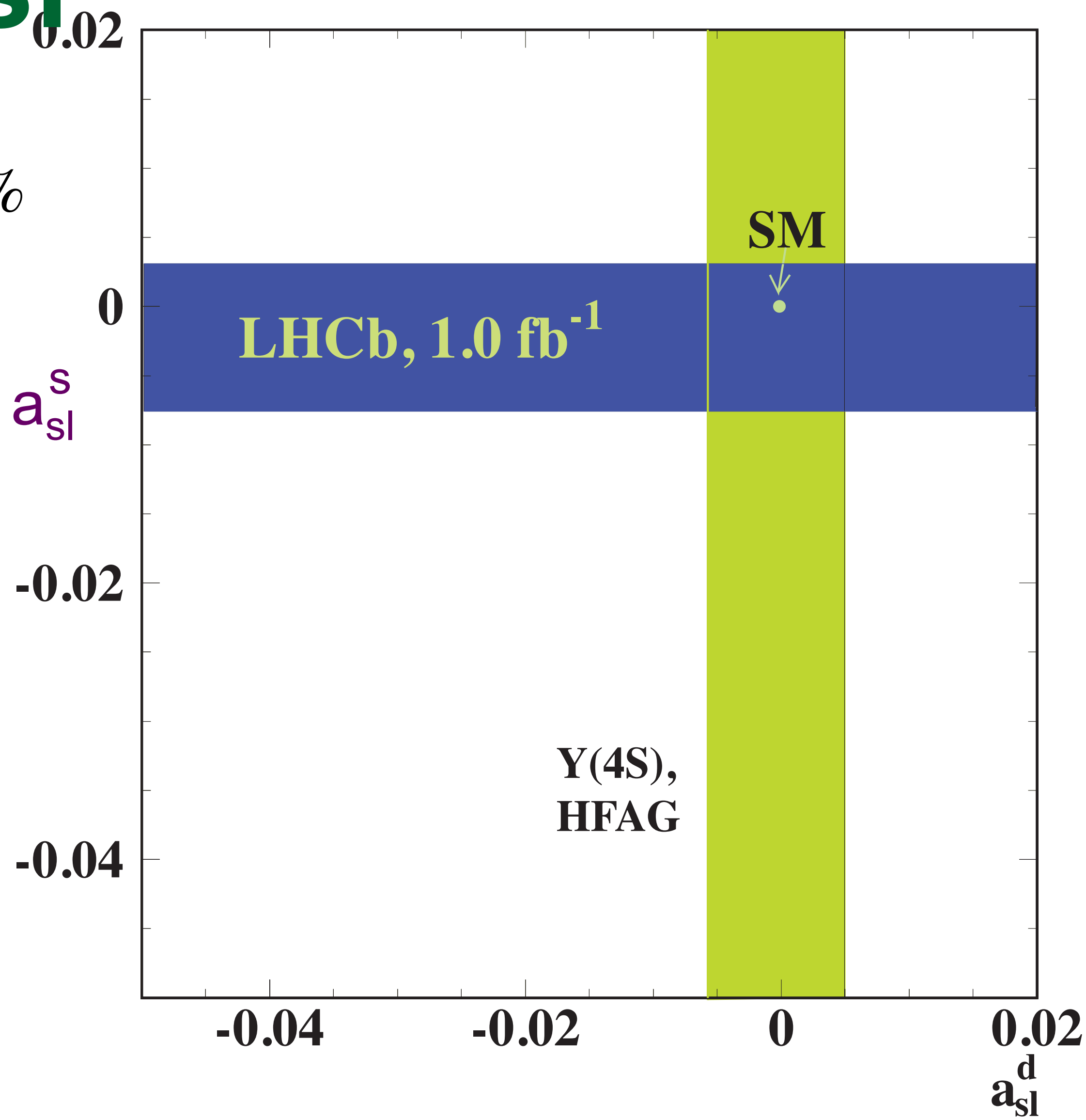
- LHCb finds

$$a_{sl}^{s} = (-0.24 \pm 0.54 \pm 0.33)\%$$

- B-factory

$$a_{sl}^{d} = (-0.05 \pm 0.56)\%$$

- Results consistent with SM
- Expect ϕ_s to grow as $\sin[2|\beta_s|+\arg(M_{12}^{s})]$ for finite a_{sl}.



CPV in Charm

- Expect largest effects in Cabibbo Suppressed Decays. COULD REVEAL NP (see Grossman Kagan & Nir arXiv:1204.3557)
- Define: $A_{CP}(D \to f) = \frac{\Gamma(D \to f) - \Gamma(\bar{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\bar{D} \to \bar{f})}$, if *f* is a CP eigenstate then $f = \bar{f}$
- Current data mainly from LHCb, CDF & Belle show

$$\Delta A_{CP} \equiv A_{CP}\left(K^+K^-\right) - A_{CP}\left(\pi^+\pi^-\right) = \left(-0.74 \pm 0.15\right)\%$$

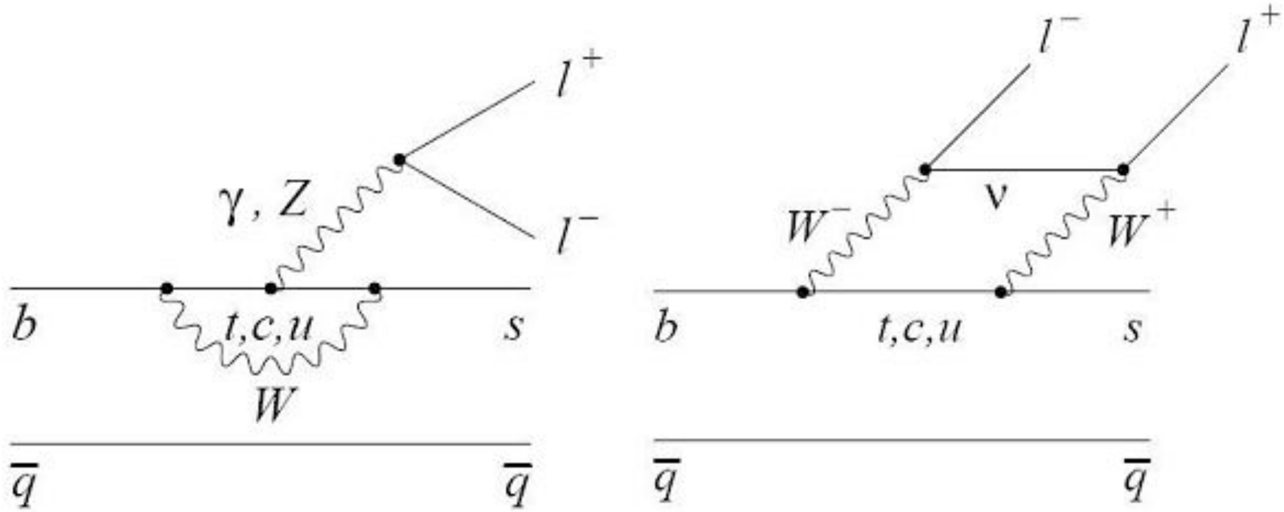
- A 4.5 σ effect

(|| talks Tico, Tonelli) & Ko

- Both SM & NP explanations are prolific
- Choose to treat this as a limit on NP: 1%>-ΔA_{CP}>0%

$B \to K^{(*)} \ell^+ \ell^-$

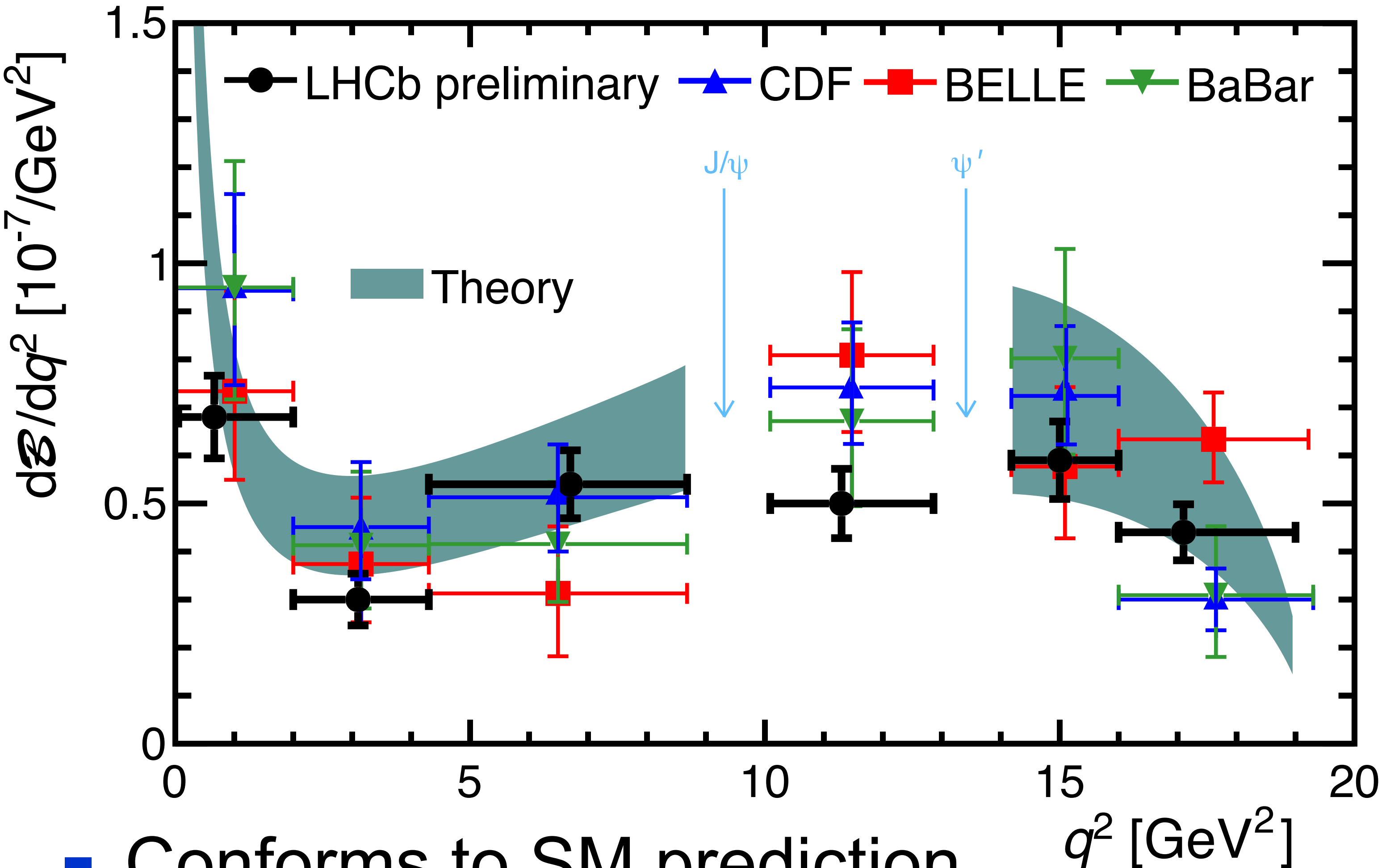
- Similar to $K^*\gamma$, but more decay paths



+ new particles in loops

- Several variables can be examined, e.g. muon forward-backward asymmetry, A_{FB} is well predicted in SM

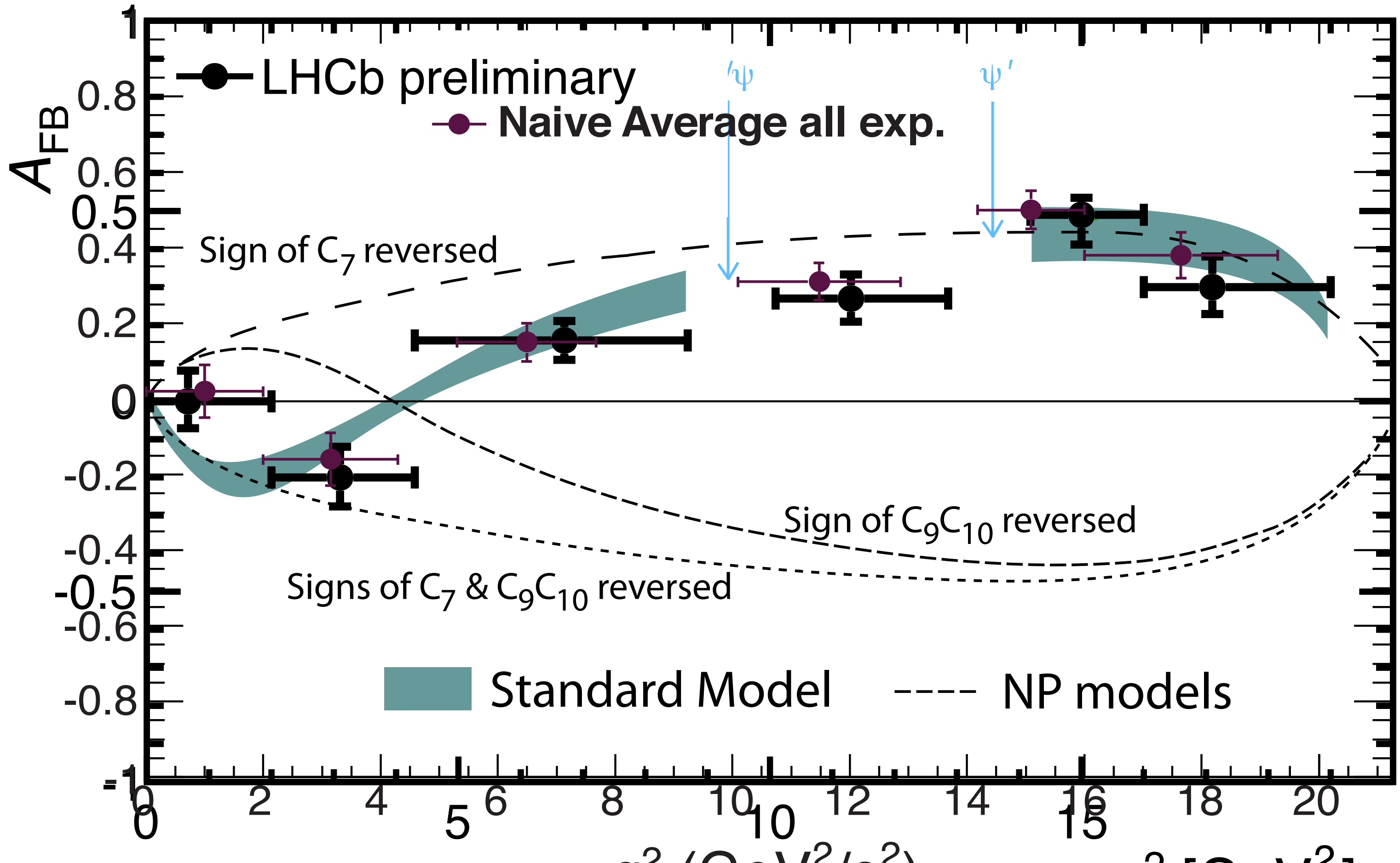
$B^o \rightarrow K^{*o} \ell^+ \ell^-$



LHCb || Gallas Torreira, BaBar || Eigen, CDF|| Miyake, Belle
PRL 103, 171801 (2009)

- Conforms to SM prediction

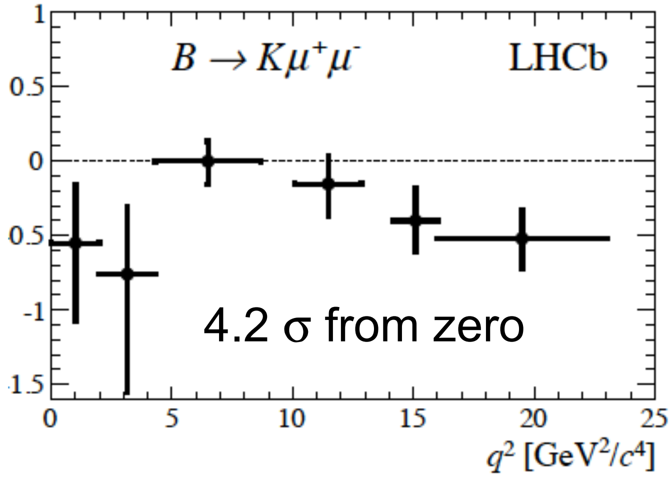
Forward-Backward asymmetry

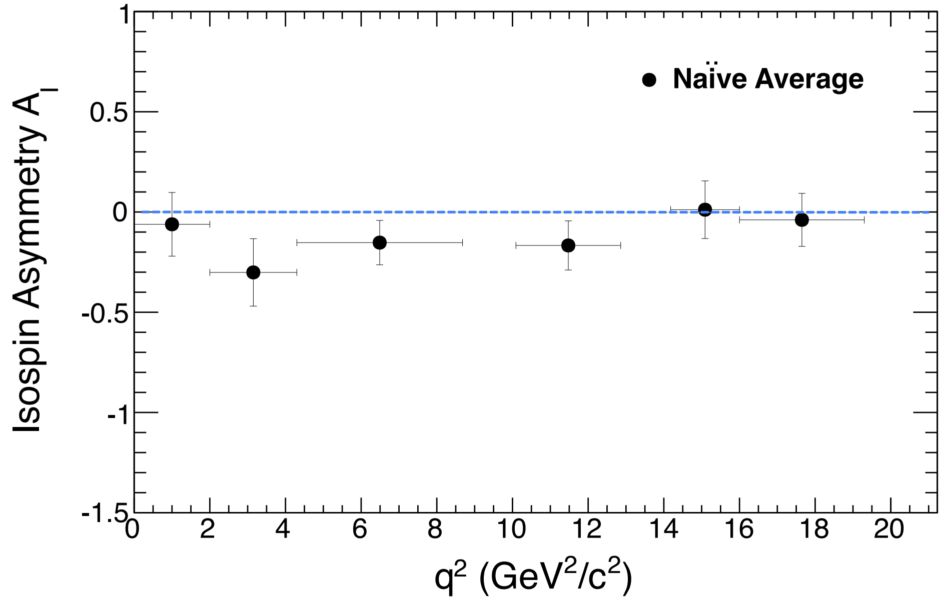


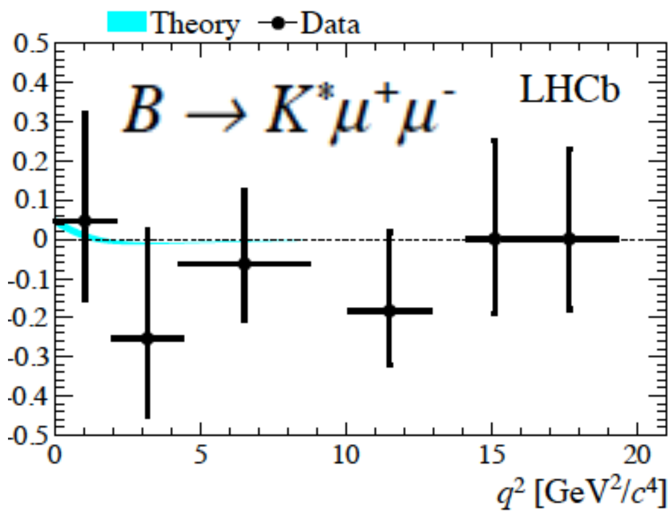
No evidence of deviation from SM so far

Isospin asymmetry

$$\frac{\Gamma(B^0 \to K^{(*)0}\mu^+\mu^-) - \Gamma(B^+ \to K^{(*)+}\mu^+}{\Gamma(B^0 \to K^{(*)0}\mu^+\mu^-) + \Gamma(B^+ \to K^{(*)+}\mu^+}$$







Not SM, but no NP model yet. Annihilation diagram only for B^-, but why the difference for K^* & K?

Other Processes

- Other processes probe different operators
  - Time dependent CPV in $B^o \to K^*\gamma$, $K^* \to K_s\pi^o$, is given by

$$\frac{\Gamma(\bar{B}^0(t) \to \bar{K}^{*0}\gamma) - \Gamma(B^0(t) \to K^{*0}\gamma)}{\Gamma(\bar{B}^0(t) \to \bar{K}^{*0}\gamma) + \Gamma(B^0(t) \to K^{*0}\gamma)} = S_{K^*\gamma} \sin(\Delta M_d t) - C_{K^*\gamma} \cos(\Delta M_d t)$$

where $S_{K^*\gamma}$= -2.3% in SM

- For Generic NP

$$S_{K^*\gamma} \simeq \frac{2}{|C_7|^2 + |C_7'|^2} \mathrm{Im}\left(e^{-2i\beta} C_7 C_7'\right)$$

- Data, BaBar & Belle (-16±22)%, still useful even with the large error

Rare Decays - Generic

- $$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i (C_i O_i + C_i' O_i') + \text{h.c.}\ .$$
- $C_i O_i$ for SM, $C_i' O_i'$ are for NP. Operators are for $P_{R,L} = (1 \pm \gamma_5)/2$

$$O_7 = \frac{m_b}{e} (\bar{s}\sigma_{\mu\nu} P_R b) F^{\mu\nu}, \qquad O_8 = \frac{g m_b}{e^2} (\bar{s}\sigma_{\mu\nu} T^a P_R b) G^{\mu\nu\, a},$$

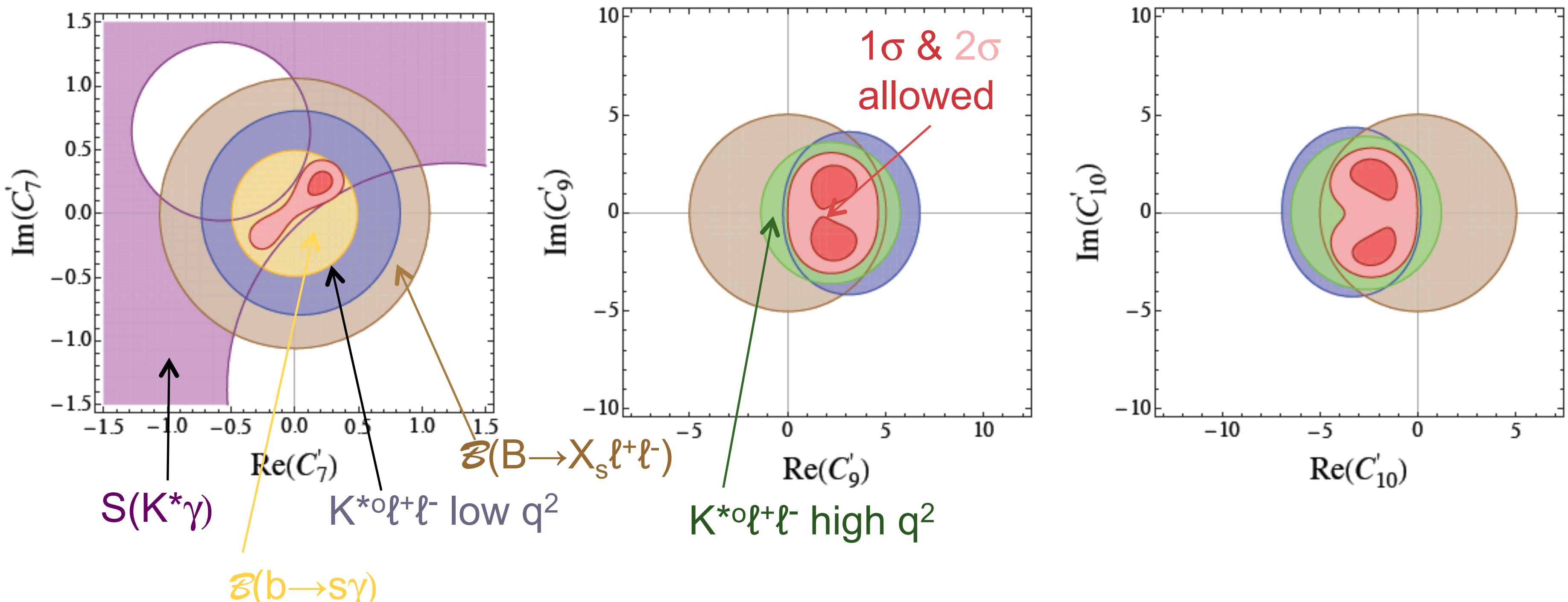
$$O_9 = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,, \qquad O_{10} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,,$$

$$O_S = m_b (\bar{s} P_R b)(\bar{\ell}\ell)\,, \qquad O_P = m_b (\bar{s} P_R b)(\bar{\ell}\gamma_5 \ell)\,,$$

- $O' = O$ with $P_{R,L} \rightarrow P_{L,R}$
- Each process depends on a unique combination

Common Analysis

- APS ≡ W. Altmannshofer, P. Paradisi & D. M. Straub arXiv:1111.1257v2

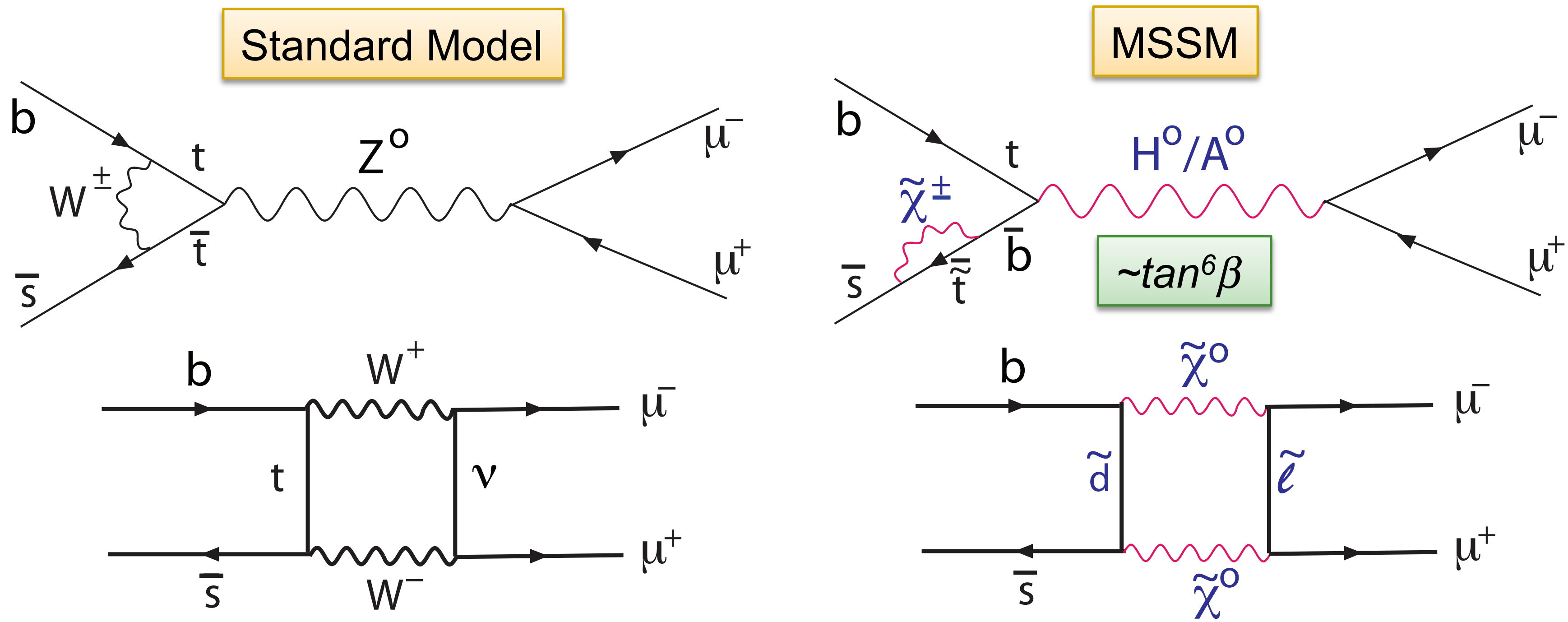


- Many more such generic constraints

$B_s \to \mu^+\mu^-$

- SM branching ratio is $(3.2\pm0.2)\times10^{-9}$ [Buras arXiv: 1012.1447], NP can make large contributions.

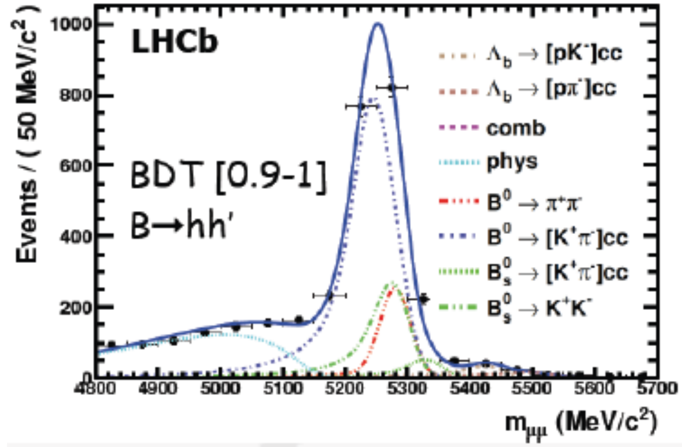
Note, K. De Brun arXive:1204.1737 show that B theory needs to be raised by $1/(1-y_s)$

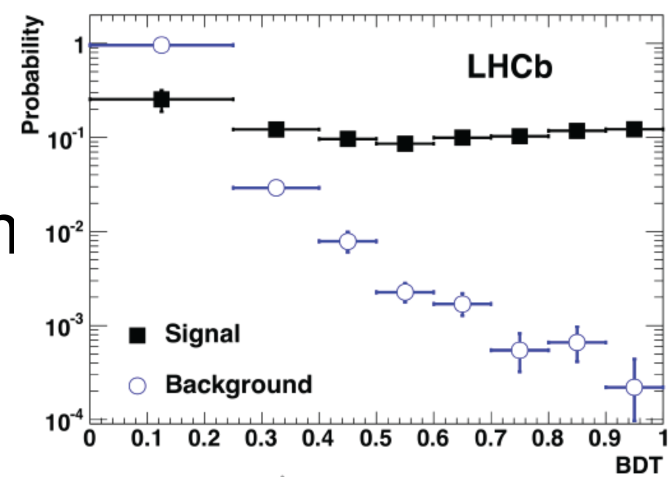


- Many NP models possible, not just Super-Sym

Discrimination

- LHCb & CDF use $B \rightarrow h^+h^-$ to tune cuts. They use a multivariate analysis
- Other variables to discriminate against bkgrd : B impact parameter, B lifetime, B p_t, B isolation, muon isolation, minimum impact parameter of muons, …
- CMS & ATLAS use f_s/f_d from LHCb



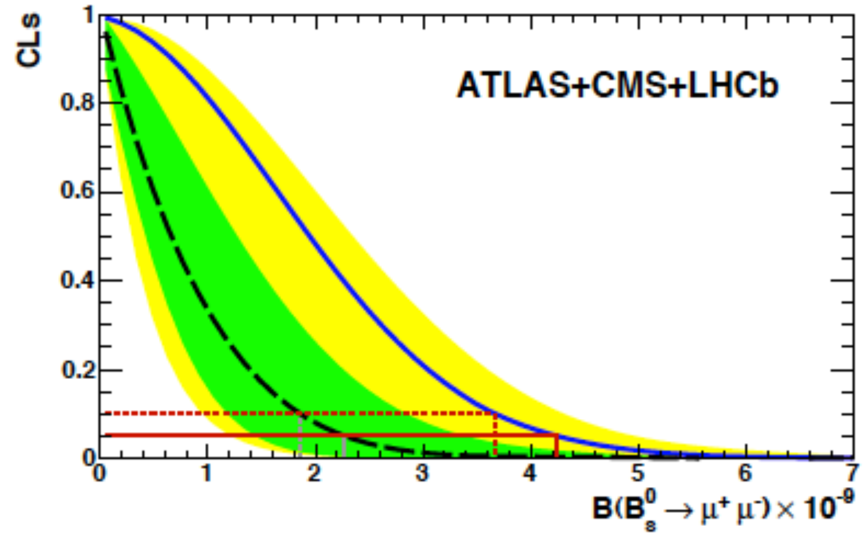


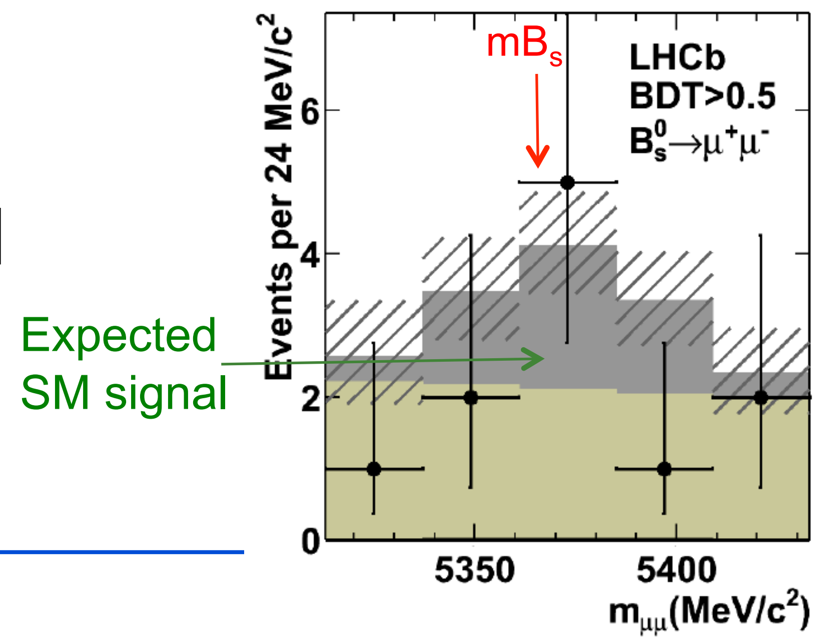
See ICHEP talk of M. Perrin-Terrin

ATLAS+CMS+LHCb

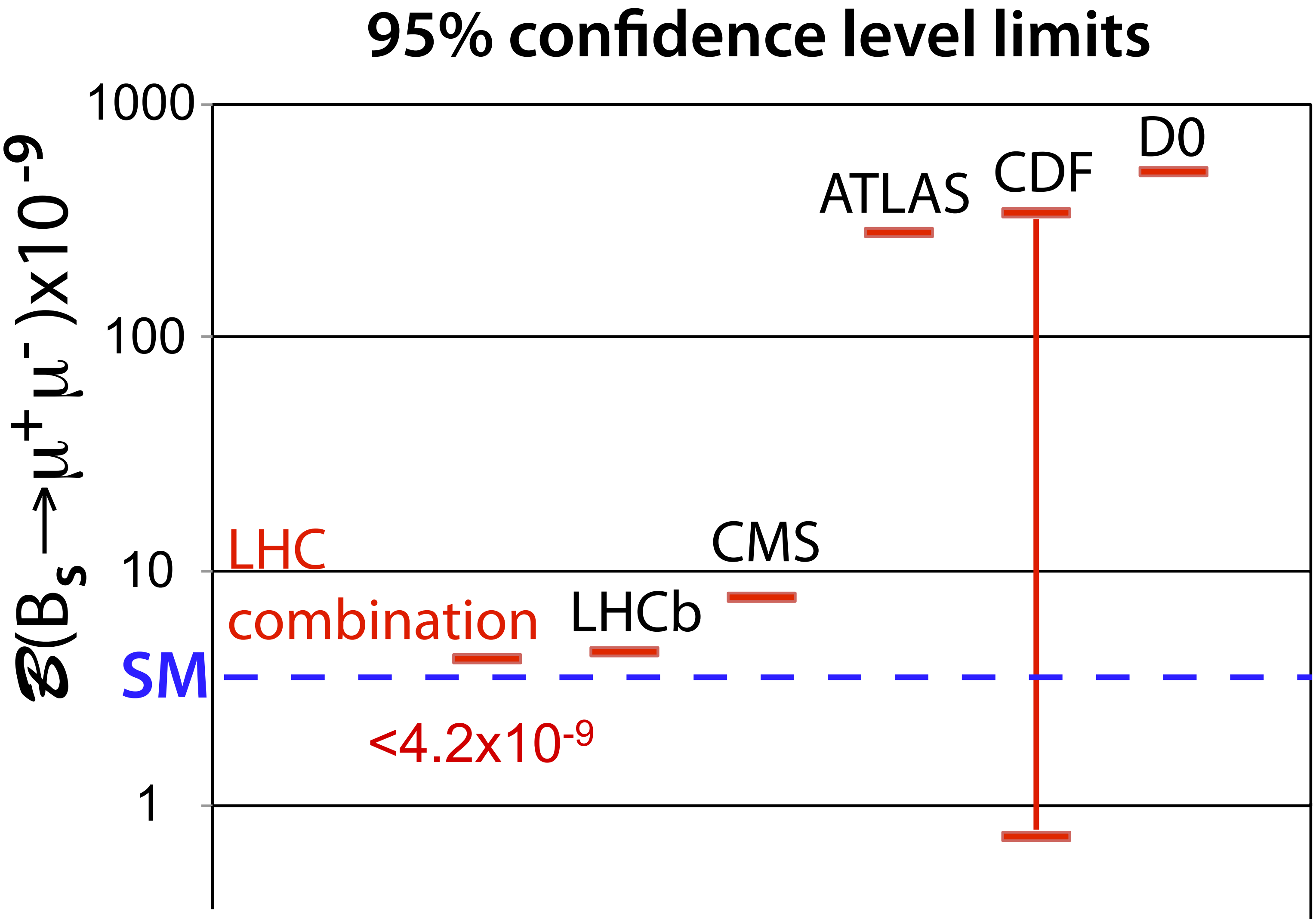
- CLs for bkgrnd only, dashed line is the expectation, blue curve show the measurement, red the 95% cl limit
- LHCb data show slight excess consistent with SM
- Also

  $\mathcal{B}(B_d \to \mu^+\mu^-) < 8.1 \times 10^{-10}$





Results


95% confidence level limits
$\mathcal{B}(B_s \to \mu^+\mu^-) \times 10^{-9}$
1000
100
10
1
ATLAS
CDF
D0
CMS
LHCb
LHC
combination
SM
<4.2x10^{-9}

Implications

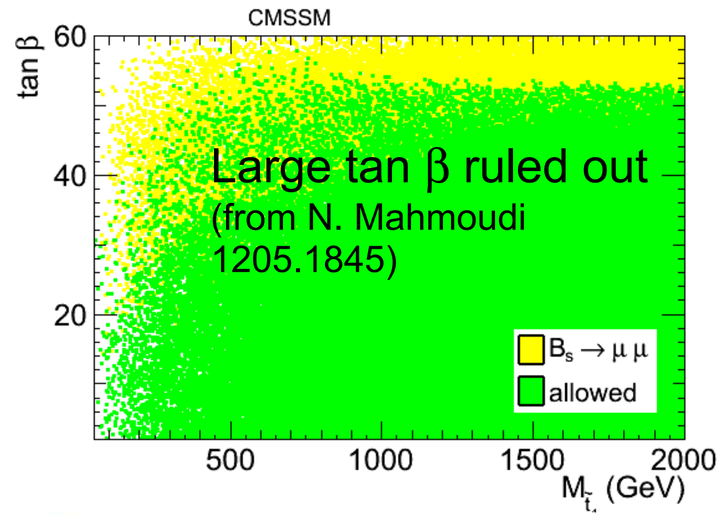
- "LHC" limit
  - $<4.2\times10^{-9}$ @95% CL
  - This is 1.2 times SM value
- Set serious limits in NUHM1 SUSY model
- Other LHCb results

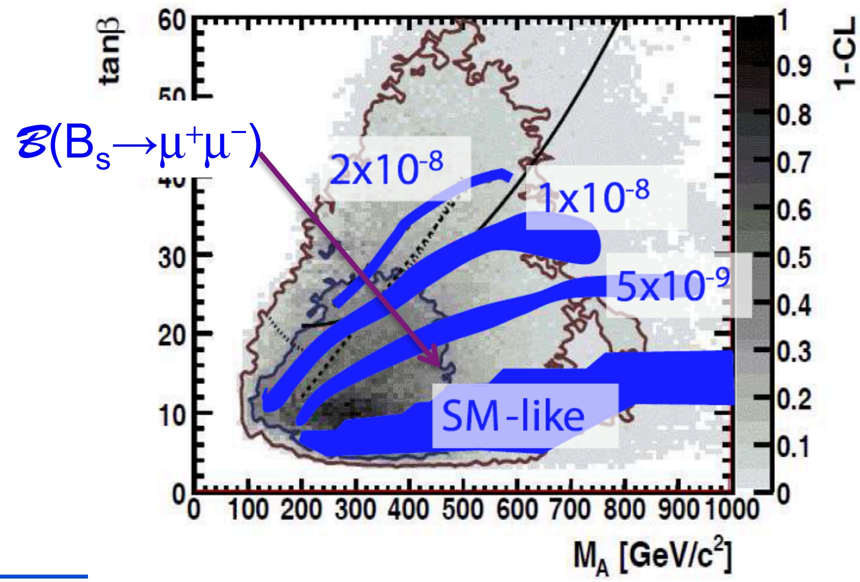
$\mathcal{B}(B_s\rightarrow\mu^+\mu^-\mu^+\mu^-)<1.3\times10^{-8}$

$\mathcal{B}(B_d\rightarrow\mu^+\mu^-\mu^+\mu^-)<5.4\times10^{-9}$

Predicted via "portals"

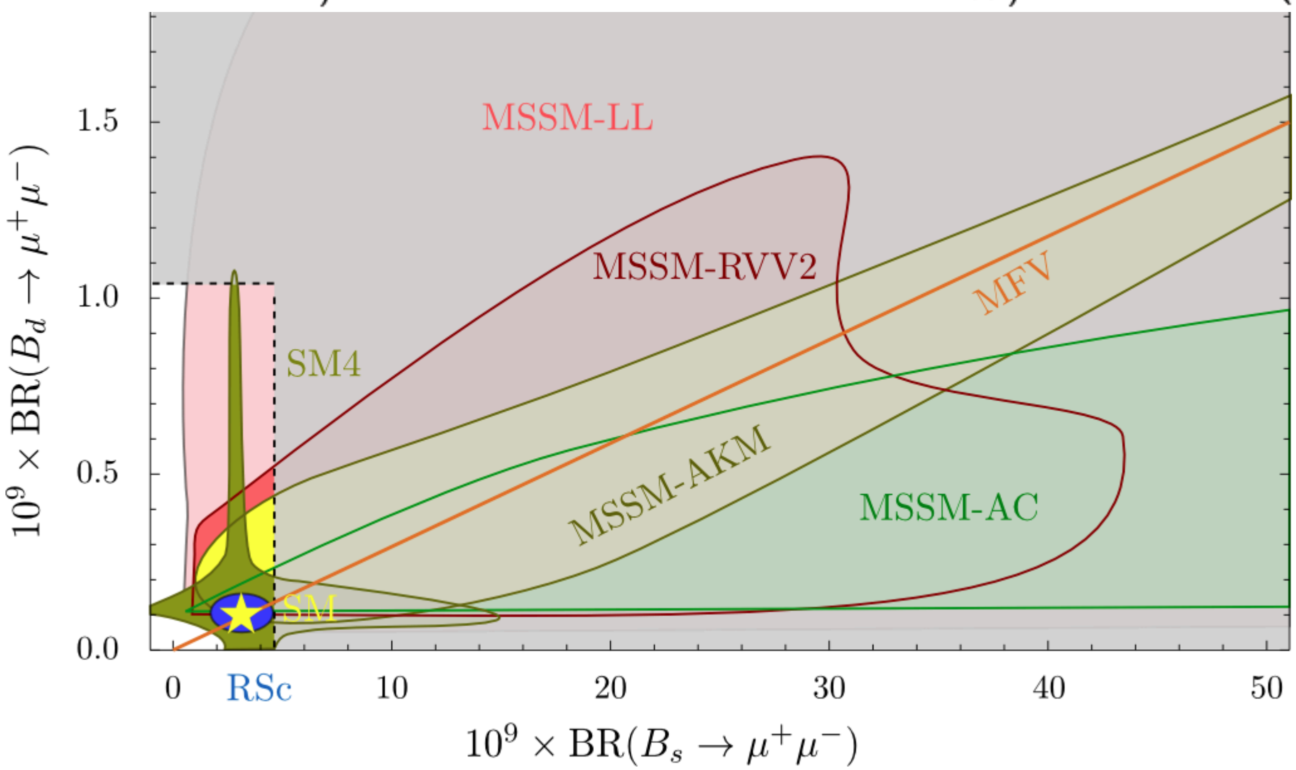
see arXiv:0911.4938





Implications II

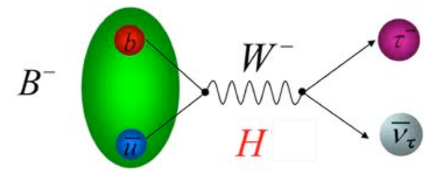
David Straub, Rencontres de Moriond EW, La Thuile (2012)



The 125 GeV Higgs observations kills off 4th generation models as the production cross-section would be 9x larger & decays to $\gamma\gamma$ suppressed

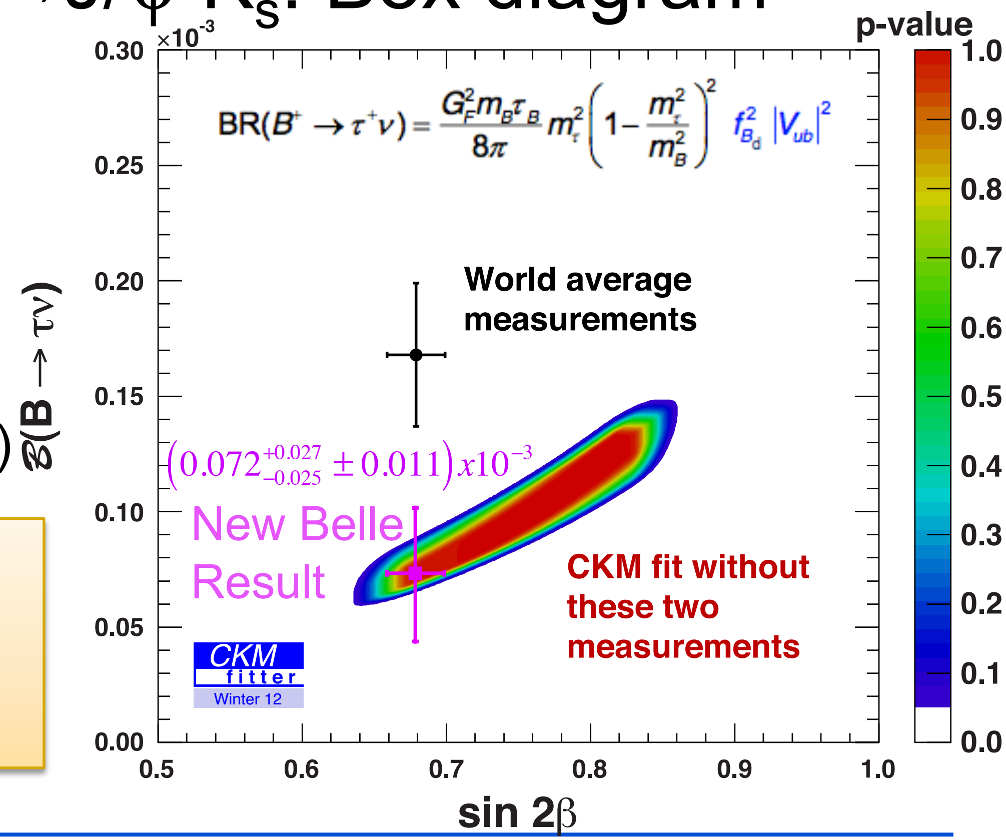
$B^- \to \tau^- \bar{\nu}$ problem?

- $B^- \to \tau^- \nu$, tree process:



Can be new particles instead of W^- but why not also in $D^+_{(s)} \to \ell^+ \nu$?

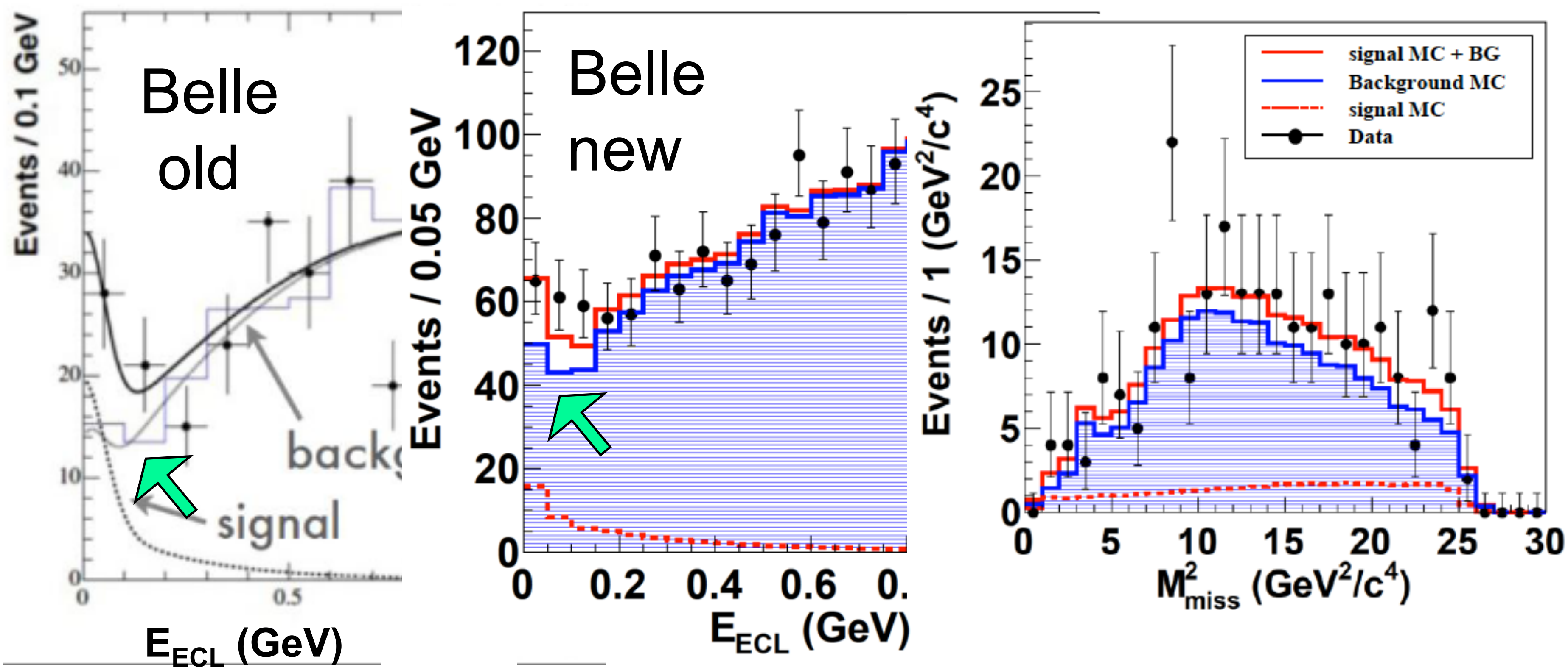
- $\sin 2\beta$, CPV in e.g. $B^o \to J/\psi\, K_s$: Box diagram
- Measurement not in good agreement with SM prediction based on CKM fit(Yook ICHEP talk)



Discrepancy may be resolved; what caused the change?

Peaking Backgrounds

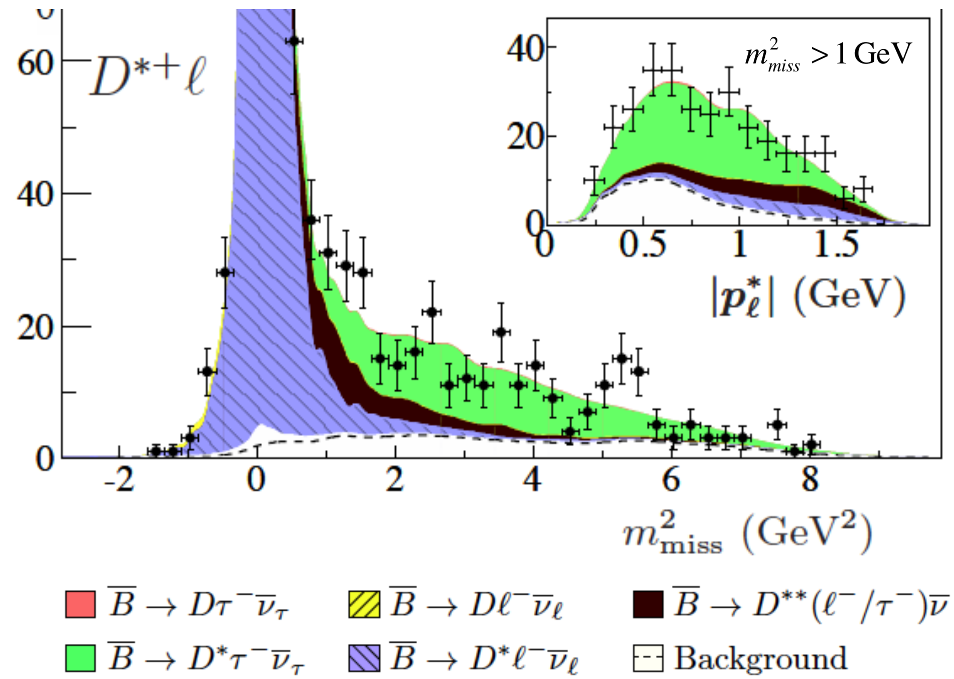
- Since $e^+e^- \rightarrow B^+B^-$, analysis uses reconstruction of B^+, detection of $\tau^- \rightarrow$ one track & small extra E



 New analysis uses hadronic tags only, see || talk of Y. Yook

$B \to D^{(*)}\tau\nu$

- Also, tree level –new BaBar result
- Similar to $B^- \to \tau^-\nu$ analysis: fully reconstruct one B, keep events with an additional $D^{(*)}$ plus an e^- or μ^-.



- Signal is wide, background, especially $D^{**}\ell\,\nu$, needs careful estimation

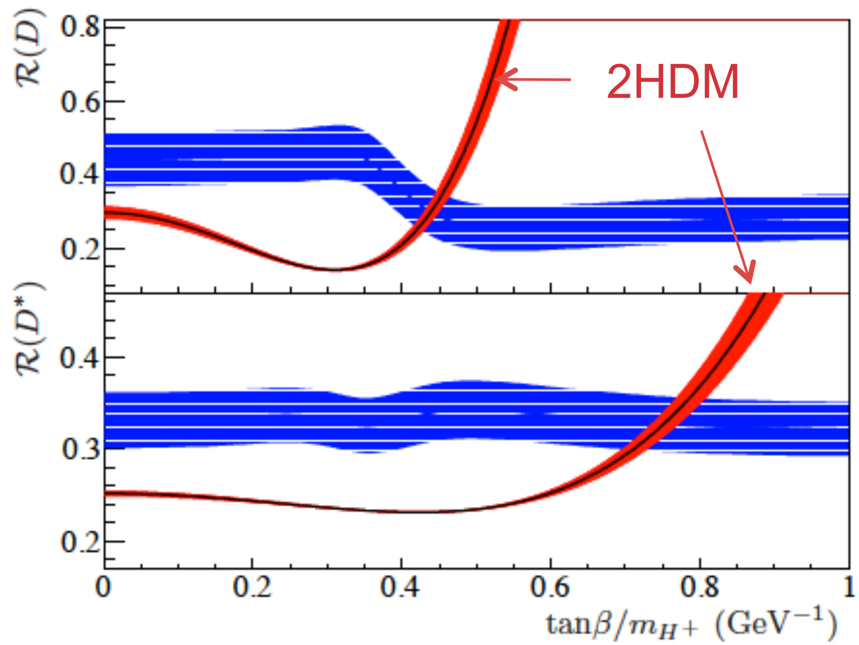
BaBar results

- Results given in terms of ratio to $B \to D^{(*)} \ell \nu$

	SM Theory	BaBar value	Diff.
R(D)	0.297±0.017	0.440±0.058±0.042	+2.0σ
R(D*)	0.252±0.003	0.332±0.024±0.018	+2.7σ

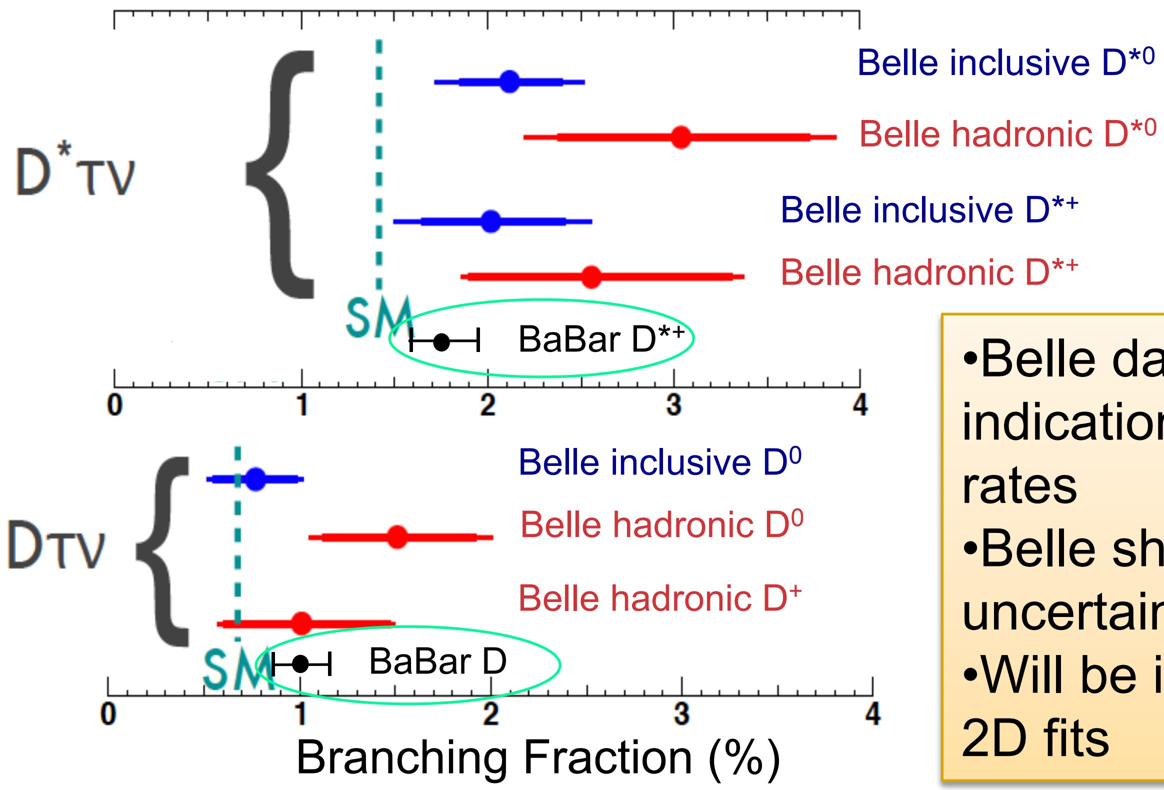
- Sum is 3.4σ above SM
- Also inconsistent with type II 2HDM

  (see De Nardo ICHEP talk)



Belle Results

- Two types of analysis, hadronic tags (arXiv: 0910.4301) similar to BaBar and also “inclusive tags” (A. Matyja et. al, PRL 99,191807 (2007)).



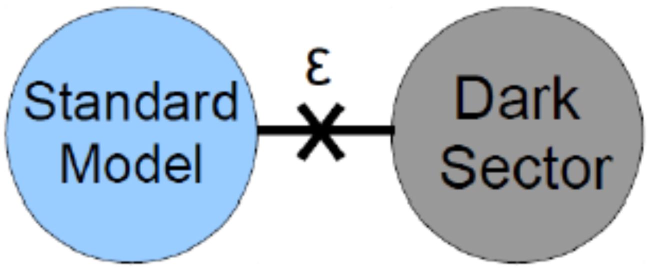
•Belle data currently support BaBar indication of larger than expected rates
•Belle should be able to reduce uncertainties to the BaBar level
•Will be interesting to see results of 2D fits

The Dark Sector

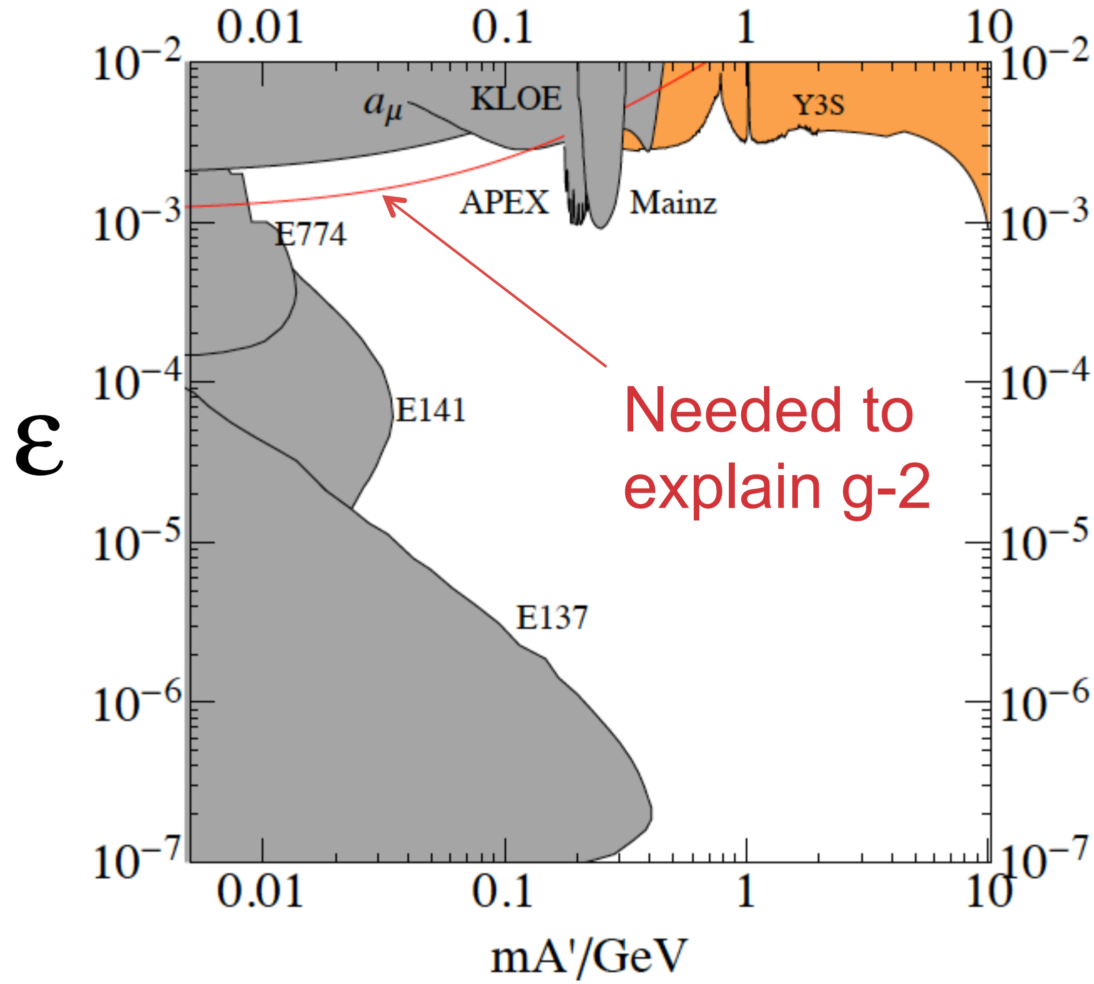
- Could it be that there are 3 classes of matter?
  - SM particles with charges [SU(3)xSU(2)xU(1)]
  - Dark matter particles with "dark" charges
  - Some matter having both ("mediators")
- Searches for "dark photons"
  - A mediator, couples to b-quarks (see arXiv:056151 hep/ph)
  - BaBar $\mathcal{B}(\Upsilon(1S)\rightarrow \text{invisible})<3\times10^{-4}$ @ 90% cl
  - Other experiments

Search Summary

- Parameterize by mixing ε



- Dark photon mass mA´

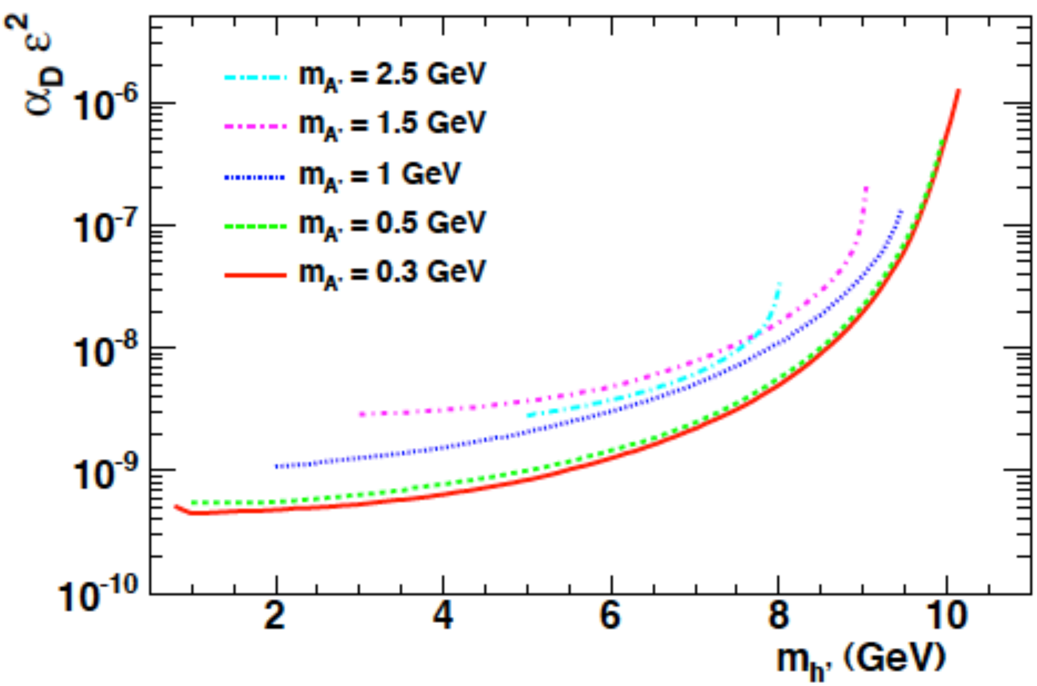


From B. Echenard arXiv:1205.3505

Dark Higgs

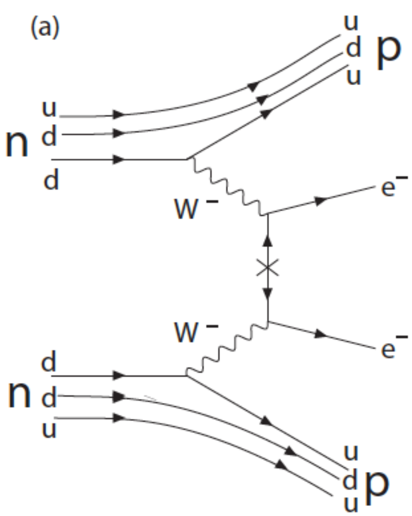
- BaBar search for $e^+e^- \rightarrow h'A'$, $h' \rightarrow A'A'$
- A' is looked for in e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$ & hadrons
- Limits parameterized in terms of mixing ε & dark matter coupling α_D

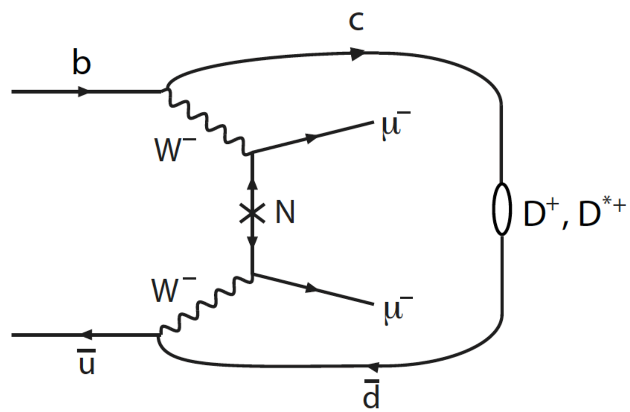
- Nothing found, upper limits set at 90% cl:



Majorana ν's

- Several ways of looking for presence of heavy ν's (N) in heavy quark decays if they Majorana (their own anti-particles) and couple to "ordinary" ν's
- Modes analogous to ν–less nuclear β decay





Simplest Channels:
$B^- \to D^+ \ell^- \ell'^-$ &
$B^- \to D^{*+} \ell^- \ell'^-$
ℓ^- & ℓ'^- can be e^-, μ^- or τ^-.

Limits on $D^{(*)+}\ell^- \ell'^-$

- Upper limits in e^-e^- mode not competitive with nuclear β decay
- Others unique since measure coupling of Majorana ν to μ^-

Mode	Exp.	u. l. x 10^{-6}
$B^- \to D^+ e^- e^-$	Belle	< 2.6
$B^- \to D^+ e^- \mu^-$	Belle	< 1.8
$B^- \to D^+ \mu^- \mu^-$	Belle	< 1.0
$B^- \to D^+ \mu^- \mu^-$	LHCb	< 0.69
$B^- \to D^{*+} \mu^- \mu^-$	LHCb	< 3.6

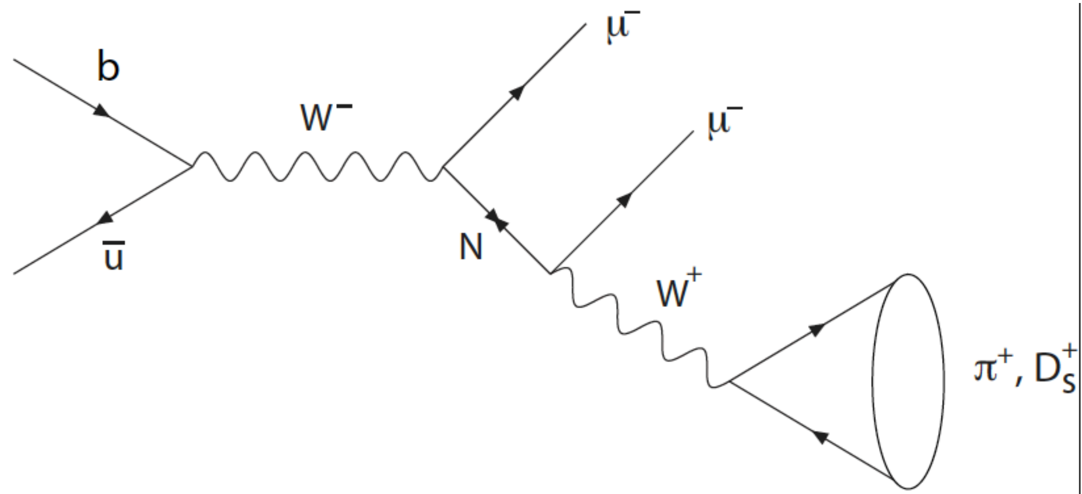
Belle [arXiv:1107.064]

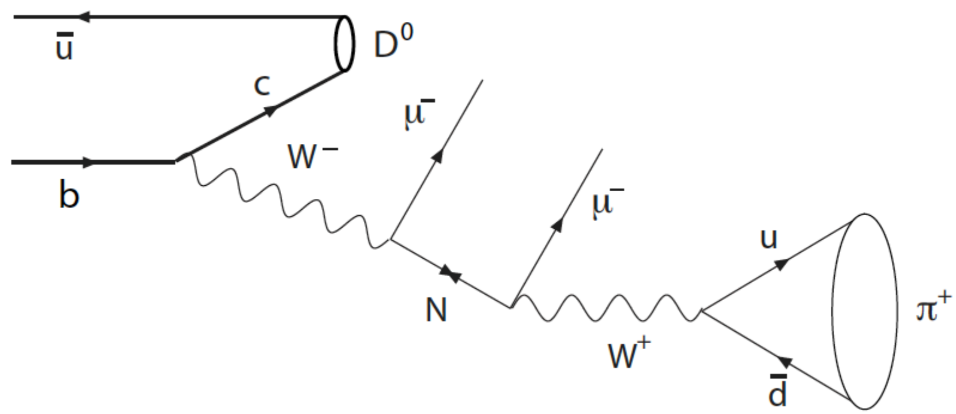
On-Shell ν

- Can also look for Majorana ν (N), where $N \to W^+ \mu^-$
- Several ways
- A. Atre, T. Han,

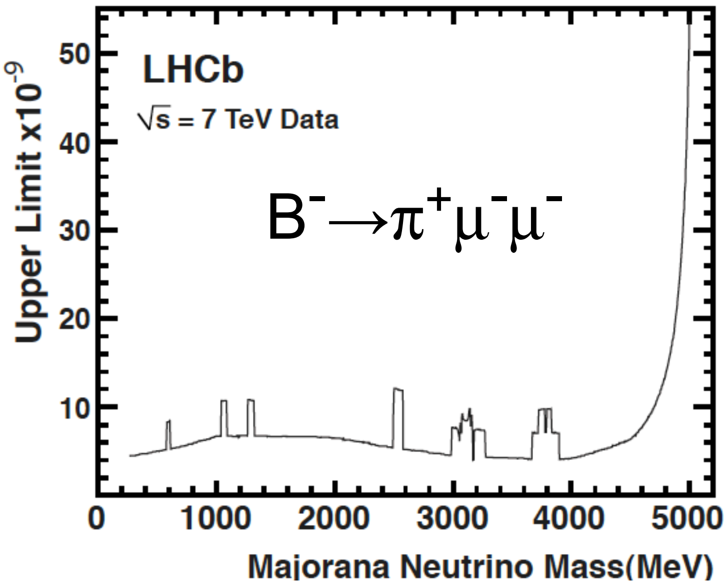
S. Pascoli, & B. Zhang [arXiv:0901.3589]

- N. Quintero, G. Lopez & Castro, [arXiv:1108.6009]



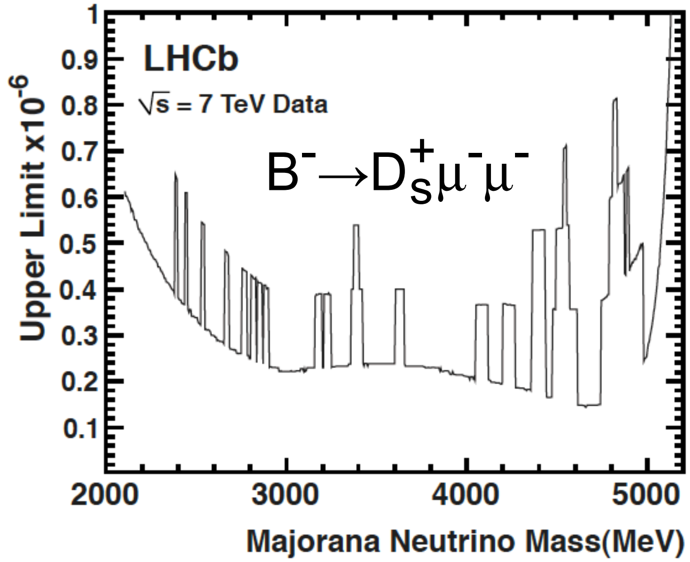


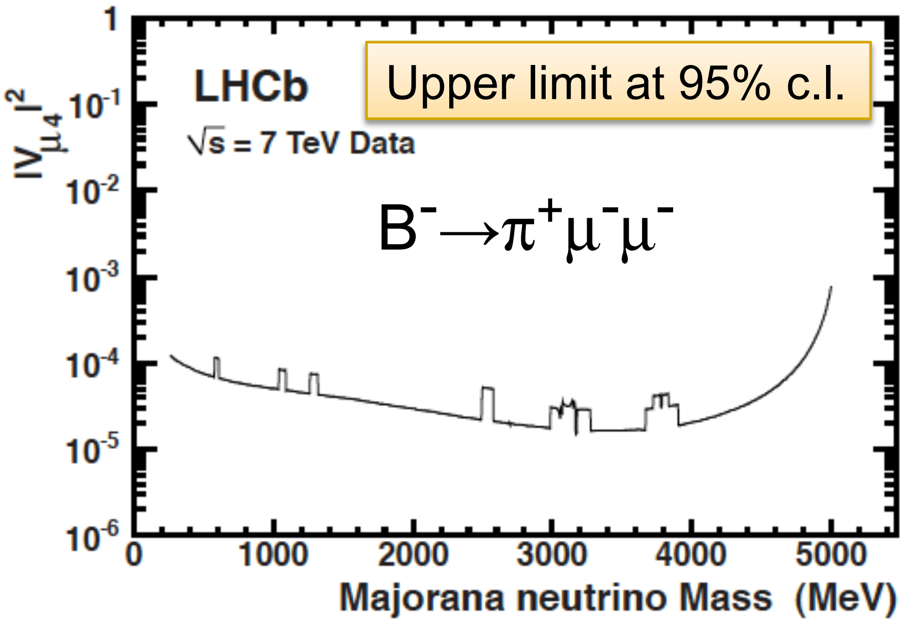
LHCb searches

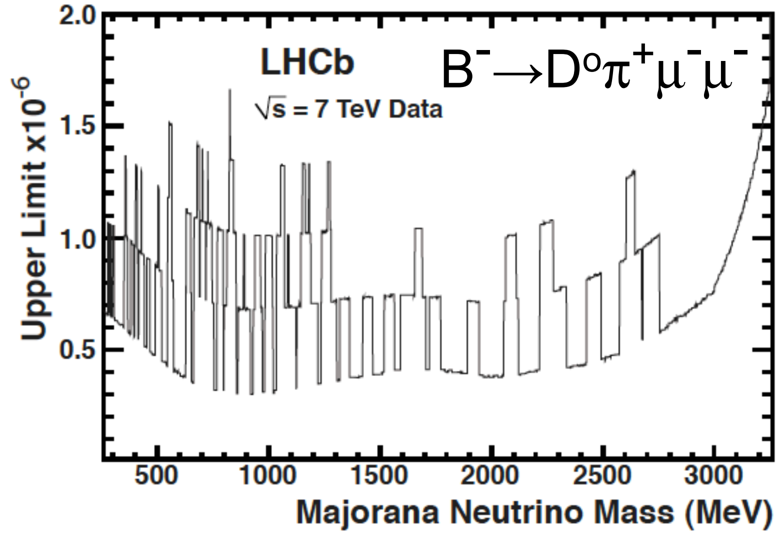


Nothing yet

Aaij, PRD 85, 112004 (2012)







Conclusions

- Although there is no compelling evidence yet for NP, Flavor physics is very sensitive to potential effects at high mass scales. All NP theories must satisfy stringent experimental constraints
- Experiments have been very effective at dispelling effects with marginal statistical significance, although a few remain. Will some stand when precision improves?
- Improving measurements such as $B_s \to \mu^+\mu^-$, $B \to K\mu^+\mu^-$, CPV: ϕ_s, etc.., may show NP effects, & need to be aggressively pursued
- We are looking forward to new flavor physics discoveries from the LHC & its upgrades, BESIII, and Super B factories
- We are looking forward to defining the next theory beyond the SM

Theory conquers

The End